

FINAL REPORT

Using Digital Acoustic Recording Tags to Detect Marine
Mammals on Navy Ranges and Study their Responses
to Naval Sonar

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Peter L. Tyack
Woods Hole Oceanographic Institution

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Acronyms

ADC – analog-to-digital converter
ADCP – acoustic Doppler current profiler
ADF – automatic direction finder
AGISC – Ad-Hoc Group on the Impact of Sonar on Cetaceans
ATS – Advanced Telemetry Solutions
AUTEC - Atlantic Undersea Test and Evaluation Center
AUV – Autonomous Underwater Vehicle
BRS - Behavioral Response Study
CEE – Controlled Exposure Experiment
DECAF – Density Estimation for Cetaceans from Passive Acoustic Fixed Sensors
dB – decibel
DSP – Digital Signal Processor
DTAG – Digital Acoustic Recording Tag
DTW – dynamic time warping
ECG – Electrocardiogram
eNGOs - Environmental Non-Governmental Organizations
FET – field effect transistor
GCP – group clicking period
GLM – generalized linear modeling
GPS – Global Positioning System
Hz - Hertz (cycles per second)
IACMST - Inter-Agency Committee on Marine Science and Technology
ICES - International Council for Exploration of the Seas
ICI – inter-click interval
Ir – infra-red
IMU – inertial measurement unit
kHz – kiloHertz
LZT - lead zirconate titanate
MEMS – micro-machined electro-mechanical system
MFA – Mid-frequency Active

MHz – megaHertz
MOSFET - metal oxide silicon field effect transistor
ms – millisecond
MV – Motor Vessel
Nm – nautical mile (1.85 km)
NMFS - National Marine Fisheries Service
NOOPP – National Oceanographic Partnership Program
NRC - National Research Council
NUWC – Naval Undersea Warfare Center
OEM – original equipment manufacturers
ONR – Office of Naval Research
PAM – passive acoustic monitoring
PC – personal computer
PCB – printed circuit boards
PRN – Pseudorandom Noise
PVC - polyvinyl chloride
RIMPAC – Rim of the Pacific Exercise
RL – Received Level
RI – Rhode Island
RTI – referred-to-input
RV – Research Vessel
SERDP - Strategic Environmental Research and Development Program
SL – Source Level
SNR – signal to noise ratio
SPL – Sound Pressure Level
TDOA – time difference of arrival
TOTO - Tongue of the Ocean
TTS – Temporary Threshold Shift
USB – universal serial bus
V2 – version 2
V3 – version 3
VHF – Very High Frequency
WHOI – Woods Hole Oceanographic Institution

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Keywords

Marine mammals, monitoring, effects of noise, anthropogenic sound, abundance, behavior, Defense activities

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the most cryptic species on the planet, and the recognized need for a precautionary approach given the animals' expected reactions to the kinds of sounds being used. It took a multi-skilled team to balance these varied challenges. We are grateful to all individuals for playing their part with professionalism and dedication.

Abstract

This project developed methods and tools to monitor cetaceans including species of beaked whale that mass strand during some naval sonar exercises, defined the acoustic exposures that start to pose a risk, and developed methods to study how beaked and other whales respond to sonar and other sounds.

The objectives included the following:

- Quantify the probability of detecting beaked whales by listening to the vocalizations of tagged whales using hydrophones on a navy underwater range
- Develop methods and conduct studies on the effect of sonar and other sounds on beaked and other whales. Define exposure parameters that pose risk to beaked whales. Test whether this risk extends to other signals and other species

The technical approaches were:

- Work with NUWC to locate beaked and other whales, tag them, and compare tag data on vocalizations with detections on range hydrophones to estimate probability of detection as a function of range and orientation of the tagged whale.
- Develop tagging techniques and field efforts to enable observational techniques or experiments that use the tag to monitor reactions of marine mammals to exposures of manmade noise.
- Develop, bench test, and build a new tag design and perform field evaluation of the new tags

All of these objectives were achieved using the technical approaches listed. In collaboration with David Moretti's group at NUWC-Newport, we validated the probability of detecting beaked whale clicks from Blainville's beaked whales tagged on the AUTEC range as a function of range and aspect. SERDP funded work also provided the basis for studying passive acoustic detection of Cuvier's beaked whale. These results have formed the basis of major advances in development by the NOPP-funded DECAF project of methods to estimate the absolute density and number of beaked whales based on passive acoustic detection of their vocalizations.

The Behavioral Response Study (BRS) in 2007 and 2008, funded in part by SERDP-1539, was able to meet the second SERDP objective. These studies identified a statistically significant response from tagged beaked whales exposed to playback of sound, and has developed and validated a method to associate acoustic exposure with a safe response.

The lack of ability to measure exposure and behavioral response directly in marine mammals is a significant obstacle to detecting and interpreting responses and to establishing dose:response relationships. A critical part of the proposal was to design, develop and build a new version 3 of the DTAG, called DTAG-3, with features critical for enabling observational studies on effects of sound on cetaceans. We have succeeded in completing the proposed development of the DTAG-3, which occupies about 50% of the volume of the existing DTAGs, but has a greatly increased

recording time, and contain innovative new GPS and swim speed sensoring. We tested and evaluated the new tags on Navy-relevant deep-diving marine mammal species in the wild.

This project have helped to define how beaked whales respond to sonar, what acoustic exposures elicit responses, and has developed methods and tools that are being used to help monitor marine mammals and how they respond to sound.

Objectives

The technical objectives for this project included the following:

1. Work with NUWC to locate beaked and other whales, tag them, and compare tag data on vocalizations with detections on range hydrophones to estimate probability of detection as a function of range and orientation of the tagged whale.
2. Develop methods and conduct studies on the effect of sonar and other sounds on beaked and other whales.
3. Develop tagging techniques and field efforts to enable observational techniques or experiments that use the DTAG to monitor reactions of marine mammals to exposures of manmade noise. We proposed to complete the development, bench testing, and field evaluation of the new tag design and to build a quantity of tags for field evaluation

1. Validate PAM and quantify Probability of Detection

The tags can record orientation and vocalizations of the whales, which can then be compared to detections on nearby hydrophones to validate probability of detection calculations. In collaboration with David Moretti's group at NUWC-Newport, Ward et al. (2008) used this method to validate the probability of detecting beaked whale clicks from a beaked whale tagged on the AUTEC range as a function of range and aspect. The data used for this initial study stemmed from years of SERDP funded effort tagging, data that enabled efforts to quantify and validate the probability of detecting Blainville's beaked whales, *Mesoplodon densirostris*, on the AUTEC underwater range. SERDP also funded work tagging Cuvier's beaked whale, *Ziphius cavirostris*, in the Ligurian Sea, data that provided the basis for a more theoretical exploration of passive acoustic detection of deep-diving beaked whales (Zimmer et al. 2008). These results have formed the empirical basis of major advances in methods to estimate the absolute density and number of beaked whales based on passive acoustic detection of their vocalizations (Marques et al. 2009).

2. Develop methods and conduct studies on the effect of sonar and other sounds on beaked and other whales.

The objective of the effects studies is to identify safe exposure levels for beaked and other whales when they are exposed to military sonars. The DTAG was designed not only to record sounds produced by whales, but also to provide sensitive and continuous sampling of acoustic exposure from manmade sounds, along with any behavioral responses (Johnson and Tyack 2003). The current tag is best suited to experiments in which biologists control relatively short-term playbacks of sonar and other sounds under controlled conditions. The Behavioral Response Study in 2007 and 2008 has identified a statistically significant response from beaked whales exposed to playback of sound, and has developed and validated a method to associate acoustic exposure with a safe response. This meets an important goal of the SERDP proposal.

The effects study has involved the following components all of which have been successfully demonstrated:

- 1) Establish, test and refine new protocols for studying beaked whales using established sound playback experiment paradigms;
 - 2) Coordinate with range monitoring to enable use of innovative tags to detect responses of beaked and other whales to naval sonar and other sounds.
 - 3) Define responses of beaked whales, and other species of odontocete whales to MFA sonar and natural sounds such as those from killer whales; and
 - 4) Measure exposure parameters for sounds that evoke each behavioral response observed.
3. Develop tagging techniques and field efforts to enable observational techniques or experiments that use the tag to monitor reactions of marine mammals to exposures of manmade noise. Complete the development, bench testing, and characterization of the new DTAG-3 design, build a quantity of tags for field evaluation, and conduct field evaluations of the new tag.

We proposed to demonstrate the capability of using the AUTEC array to facilitate locating and tagging beaked whales. We also proposed to extend the duration of our tag attachment for several days, long enough to collect pre-exposure, exposure and post-exposure data for animals exposed to sounds on Navy ranges. The techniques are essential for observational studies and would be useful methods for the development of controlled exposure experiments. Further work was required to complete the development, bench testing, and field evaluation of the new tag design and to build a quantity of tags for field evaluation and to accelerate Navy-funded field programs. The new DTAGs were used immediately in the Navy-funded BRS and the NOPP-funded project, "Acoustic Detection, Behavior, and Habitat Use of Deep-Diving Odontocetes," both of which were dedicated to providing information for improved mitigation and passive acoustic detection. The small size and improved capabilities of the new tag met the objectives of longer duration and more detailed data from cetaceans while the improved attachment reliability will increase the efficiency of field studies.

The proposed work developing tagging capabilities including the expansion proposal for SERDP-1539 comprised three activities:

- (i) construction and bench evaluation of a quantity of DTAG-3s.
- (ii) design and assembly of tag support kits including radio tracking systems and tag interfaces.
- (iii) field evaluation of the new tag on deep diving marine mammals.

In the first phase of the project, we designed, produced and characterized a quantity of DTAG-3s for field evaluation. The tags are self-contained multi-sensor recording platforms containing 2 hydrophone channels and a set of sensors measuring depth, orientation, position and speed. The DTAG-3s are suitable for use with any cetacean of adequate size and have an audio bandwidth compatible with all currently known whale vocalizations. The DTAG-3s communicate with a standard PC via a USB interface and so will be straightforward to use in the field. The overall design of the new tag is similar enough to the older DTAG designs that the considerable body of

software, data treatments and field experience accrued in the last 8 years will be immediately applicable to the new devices. However, a number of features in the new design require additional development and characterization, specifically:

- (i) the small target size of the tag necessitated a different plastic housing and sealing method than used previously. We developed a rigid plastic machined housing that, in combination with a polyurethane over-potting, both protects the electronics and seals out saltwater. This construction replaces the three protective layers used in the DTAG-2 by a single layer, making the design simpler, more compact and enhancing the stability of acoustic sensitivity.
- (ii) the suction cups were improved to increase the attachment times and reliability of attachment. The old two-piece cup design was replaced by a smaller cup that is more robust in the field and can be manufactured outside of Woods Hole Oceanographic Institution (WHOI), which makes them cheaper to produce. In a separately funded project (funded by NOPP), we will test the factors that limit non-invasive tag attachments, including testing the new cups in pressure fixtures and on carcasses of stranded delphinids at WHOI.
- (iii) the antenna in the GPS sensor is affected by materials surrounding it, especially encapsulants and water on the outside of the package. We experimented with packaging designs around the antenna that minimize de-tuning effects and that shed water rapidly from the outside surface to maximize the duration and sensitivity of satellite observations during surfacing. The post-processing method we have developed to analyze the short GPS observations during surfacings, the enabling step in the new GPS sensor, is currently implemented as a proof of concept in Matlab but is labor-intensive to apply. The algorithm and internet searches for satellite almanac data that it requires require further automation to be easily used in the field. The resulting tool will allow rapid computation of the track of a tagged whale after tag recovery. Due to some fabrication delays, the GPS sensor on the tag, although functional, has not yet been fully evaluated in a field environment. As a result, some fine-tuning of hardware and software remains to be done.
- (iv) the speed sensor initially proposed for the DTAG-3 was based on a well-established pulse-pair reflectometry method. However, based upon advances in gyroscope technology, along with the power constraints imposed, we decided to implement a low-power, 3-axis gyroscope. Speed will now be derived by integration of the accelerometer signals after the gyroscope-derived orientation is removed.
- (v) the DTAG-3 will be supported by an improved suite of software for automatic data offloading, archiving, analysis and sharing. An integrated software interface brings together our existing tools for tag configuration, data offloading, data-driven calibration, rapid data evaluation, and metadata extraction. The methods will be documented both in the form of a user manual and in a publication describing the techniques we have developed for tag sensor data analysis.

In tandem with these developments, we proposed to increase the memory in the tag from the current 6-12 Gbytes to up to 32 Gbytes to accommodate the data from the new sensors and to extend the recording life of the tag. Lower power requirements and a denser Lithium Ion battery also support this extended recording time. The design goal, which was met, was for overall dimensions of the new tag, as mounted on a whale, to be about 150x65x30 mm (6x2.5x1.2 inches), a reduction of over 50% in the overall envelope volume compared to the DTAG-2 (the DTAG-2 has dimensions 215x100x40 mm or 8.5x3.9x1.6 inches). Smaller size and weight are the keys to more reliable delivery of the tag to agile whales and for longer attachment durations.

The next phase of the proposed work involved a field evaluation of the new tags on deep-diving cetaceans. Low-cost opportunities existed to test the tags within currently funded studies on deep diving odontocetes. These studies focus on sperm whales and beaked whale species of special interest to the Navy. We performed initial testing of the tags as a piggyback on these studies because of the low cost and high efficiency of the field sites. Tags were deployed on beaked whales and sperm whales within networks of GPS-synchronized acoustic recording buoys. The arrival times at the buoys of vocalizations from the tagged whale can be used to estimate the position of the whale independently of the dead-reckoned whale track deduced from the GPS, speed and orientation sensors on the tag. A comparison of the two tracking methods will enable fine-tuning of the dead-reckoning algorithm, an estimation of error magnitude, and will potentially identify errors in the programs.

The final task in the proposed work is to share results from the tag development. We planned to host a workshop on tag sensor design and data interpretation at an international conference on acoustics or marine mammalogy. Although a number of groups are using tags with inertial and acoustic sensors on marine animals, standard procedures for calibrating and processing the data from such sensors have not yet emerged. We have selected the fourth Biologging conference for a workshop on fine-scale on-animal movement sensing: methods, performance and limitations. An objective of the workshop is to encourage sharing of methodologies and data sets from tag-based sensors so as to foster standardization in the treatment of tag data. An outcome of this workshop will be a journal publication outlining the potentials, caveats, and best practice to adopt with tag-borne acoustical, inertial and navigation sensors. As a separate task, we continued holding the DTAG users workshop, a one-day course on field use and initial data evaluation. The course, first offered in 2006, has been well received and is available each year to all potential or current DTAG users.

Background

Evidence has accumulated that a number of species of marine mammal may be affected by the operation of sonars during Navy exercises. Responses attributed to sonar exposure include mass-strandings (Cox et al. 2006; D'Amico 1998; Evans and England 2001; Frantzis 1998), long-term habitat avoidance, and high-speed escape (Kvadsheim et al. 2007). Such strong effects could impact local populations of marine mammals, with both ecological and commercial (e.g., whale watching industry) implications, and can lead to the imposition of restrictions on Navy maneuvers. To address this problem, more information is required about both the ways in which different marine mammal species respond to anthropogenic sound, and in how to recognize and avoid concentrations of vulnerable species. A potentially powerful tool in this regard is passive acoustic detection. In many cases, marine mammals can more reliably be detected by their vocalizations than by sightings, and systems capable of detecting these sounds have application both in surveying areas prior to exercises, and in real-time mitigation during exercises. Passive acoustic detectors can be built into gliders and AUVs to provide persistent monitoring of a site or to survey large areas at low cost. However, there are currently critical information gaps thwarting the development of passive acoustic detection systems for marine mammals. Complete descriptions of the vocalization types and rates are lacking for many species including some considered especially vulnerable to anthropogenic sounds. We also know little about the environmental and social contexts in which they do and do not vocalize, making it difficult to judge the overall efficacy of passive detection. Tagging studies with acoustic recording tags, such as the DTAG, offer the most direct way of obtaining this information (Matthews et al. 2001, Marques et al. 2009).

Many meetings and workshops have been convened during the past 15 years to discuss the problem presented to marine mammals by anthropogenic sound in the oceans. In every case these meetings have concluded that the data are insufficient to develop anything other than highly precautionary, and in many cases arbitrary, approaches to the management of marine mammals in the face of apparent threats. At times the debate has become heated, acrimonious, and even destructive as different parties have attempted to assert their particular interpretation of the scant information about where the line should lie between preventing an underwater sound-producing activity and permitting it to proceed. The narrower issue of the impacts of naval sonar on marine mammals has been the focus of a series of court cases in the US, many of which have restricted naval exercises with mitigation measures of unknown benefit to cetaceans. There is an urgent need to understand the causes of these strandings and to develop ways to reduce the risk that naval sonar exercises pose to marine mammals.

During the late 1990s and continuing up to the present, a major research program focused on Temporary Threshold Shift (TTS) experiments in the belief that audiometric results could serve as a conservative and safe indicator for identifying exposures that would pose a risk of physical injury to marine mammals. The logic was that the inner ear is the organ system most sensitive to sound, and that temporary effects of underwater sound on hearing could be used as a quantitative means of predicting permanent injury from higher-level exposures. Levels of sound sufficient to cause TTS have been measured for a few individuals of a few pinniped and odontocete species (reviewed in Southall et al. 2007). TTS studies have not included beaked whales, though their audiogram (Cook et al. 2006), phylogenetic and morphological similarities to those cetaceans

tested would suggest that relatively high levels of sound exposure should be required to cause physical damage to beaked whale hearing systems. The TTS-based injury criteria (Southall et al. 2007) predict that direct acoustic injury would be unlikely to occur farther than tens of meters from operational sonars.

For the strandings that coincided with sonar exercises, there is no information on the initial location of the beaked whales that eventually stranded. However, it seems unlikely that many of the whales observed to strand in some events (e.g., D'Amico 1998 and Evans and England 2001) would have come so close to large, generally fast-moving, sonar sources within such a short time. While fewer than 200 beaked whales are known to have stranded globally during the last few decades coincident with sonar exercises, the true magnitude of the problem is generally unknown and may not be limited to just those animals actually detected during stranding events. The causal sequence leading to injury is unknown, and these effects may not be limited to MFA sonar and beaked whales. The effects are almost certainly triggered in certain conditions by exposures below those predicted to result in auditory injury based on TTS measurements. This situation creates an urgent need to understand the causal mechanism of these effects using empirical measurements of behavioral responses in situations where received sound exposures are well characterized.

A variety of hypotheses have been proposed to explain the causal chain of events from sound exposure to stranding. Very generally, there are three broad categories of hypothesis to explain current observations: 1) those that suggest that beaked whales may be physically injured by intense sonar sounds; 2) those that suggest sonar triggers a behavioral reaction that causes beaked whales to panic and swim to shore, which results in them dying from injuries associated with stranding; and (3) those that suggest sonar triggers a behavioral reaction that causes injury or death in beaked whales independent of stranding (Cox et al. 2006).

The different hypotheses for the cause of sonar-induced strandings suggest very different approaches for reducing the risk to whales from sonar exercises. In the case of hypothesized direct physical injury, no known physical effect of these sonars could injure a whale at ranges >100 meters from the sonar (Southall et al. 2007). These hypotheses would suggest a requirement for short-range monitoring and controlling the source to ensure that no beaked whale came within this danger zone. The second hypothesis, which proposes that the only risk to beaked whales of injury or death stems from stranding, leads to the conclusion that one might reduce the risk of injury by conducting sonar exercises far from the coast. Beluga whales, which are the size of beaked-whales, may show panicked flight responses to the sound of ice breaking ships at ranges of tens of kilometers (e.g., LGL and Greeneridge, 1986; Finley et al., 1990), and the geographical pattern of beaked whale mass strandings where the source location is known is consistent with possible responses at these long ranges. Taken together, these observations suggest that some form of behavioral response, perhaps even at quite low received sound levels (i.e., well below those that would invoke TTS or other sources of direct physical injury) could initiate a behavioral reaction that ultimately was responsible for beaked whale strandings. The third set of hypotheses suggests that sonar exposure may trigger a behavioral reaction in beaked whales that could injure them independent of stranding, and that either the reaction or the subsequent injury leads some of the whales to strand. If one of these third hypotheses is correct, then moving sonar exercises offshore might not reduce the risk to the whales, even though it

might reduce the likelihood that humans would detect the problem. It is essential to understand which hypothesis is correct because the mitigation measures suggested by some hypotheses may not protect whales from risk if an alternative hypothesis is true.

Another important area of uncertainty is the extent to which the responses observed are specific to beaked whales or could affect other species. In addition to atypical mass strandings of beaked whales coincident with naval exercises, there is one report that a stranding of two *Ziphius* occurred in the Gulf of California when a seismic vessel was operating tens of km away (Malakoff, 2002), another report of a live stranding of two *Ziphius* occurred near Punta Candor, Rota, Spain when a seismic vessel was operating tens of km away, and another report of a mass stranding of beaked whales concurrent with seismic survey, at a range of hundreds of km (Gentry, 2002), but the extent to which these are coincidences or represent a cause-effect relationship is unknown. There are also reports of delphinid odontocetes such as *Peponocephala electra* swimming in bays (Southall et al., 2006) or *Globicephala macrorhynchus* stranding during naval sonar exercises (Hohn et al., 2006). While these incidents provide weaker evidence for a link between sound exposure and stranding than the series of cases involving atypical mass strandings of beaked whales during MFA sonar exercises in some areas (Cox et al. 2006, Filadelfo et al. 2009), they suggest the need to test responses of these other species to sonar for comparison to responses of beaked whales, and to test responses to other sound stimuli such as those produced by airguns and low frequency sonar. The research focus tends to be on mid-frequency sonar and beaked whales because of the association between atypical mass strandings of beaked whales during sonar exercises, but it is essential also to test for effects of a variety of sound sources upon beaked whales and other species using a comparative approach with similar methodologies.

The important applied question for the research community is “what can be done to avoid, reduce or eliminate the accidental stranding of whales, or other causes of harm, that result from exposure to sonar or other sound sources.” The basic problem motivating this research effort is that until we know which acoustic exposure levels start the chain of events leading to stranding, it will not be possible to establish science-based criteria to prevent the risk of adverse impact of sonar on beaked whales. Most of the reports on marine mammals and underwater sound (National Research Council, NRC 1994, 2000, 2003, 2005; the International Council for Exploration of the Seas (ICES) Ad-Hoc Group on the Impact of Sonar on Cetaceans, AGISC 2005; and the UK Inter-Agency Committee on Marine Science and Technology, IACMST 2006) and the report of a technical workshop on beaked whales (Cox et al. 2006) recommended an experimentally-based approach to addressing the need for new and reliable data on how beaked and other whales respond to sonar and other underwater anthropogenic sounds.

The DTAG, a multi-sensor acoustic recording tag for marine mammals, was designed at WHOI in 1999 (Johnson and Tyack 2003). Since then, the tag has been applied to over 300 animals from 13 species and has produced substantial scientific results in the form of some 20 journal publications and numerous conference presentations. The current version of the DTAG, a revision of the original design made in 2002, has proven to be a versatile and highly reliable device, regularly achieving attachment durations comparable to the maximum recording time of memory on the tag, 15-20 hours. The tag has collected breakthrough data on two species of beaked whales and has been applied to other marine mammals such as orca, pilot whales,

manatees, right whales and sperm whales. In the process, a significant body of experience has been gained in the field use of the tag and in examination of data collected by the device.

There is currently increasing concern about the impact of naval activities on smaller species of cetaceans such as beaked whales and delphinids. To achieve reliable and unobtrusive tag attachments on some of these species, a smaller DTAG is required while the high frequency sounds produced by these species call for an extended recording bandwidth and memory capacity. In tandem, proposed behavioral response and habitat use studies require longer attachment and recording times than are achievable with the current version of the DTAG, the DTAG-2. These studies would also benefit from more precise localization of tagged whales than is currently possible, calling for an expanded sensor suite on the tag.

To meet these new requirements, we proposed to complete a second revision of the DTAG, creating a new third version of the DTAG, DTAG-3, designed both to reduce the size of the tag and incorporate additional features. Taking advantage of new smaller components and sensors as well as more dense memory, the design features of the new tag called for occupying less than one half of the volume of the current version. The new tag design called for an increase in memory capacity by a factor of 2.5 and the audio bandwidth to 150 kHz, sufficient for most delphinids. The reduced power consumption of the tag was designed to allow recording times of up to 4.5 days depending on the audio sampling rate. To improve the geo-referencing of tagged whales, we proposed to develop miniature GPS and swim-speed sensors for the tag. In conventional GPS sensors, continuous satellite observations of at least several seconds are required to acquire a position. However, even though small marine mammals may surface frequently, they seldom remain at the surface for such continuous periods, making conventional GPS impractical. To overcome this problem, we have developed a novel post-processing method that produces accurate positions from surfacings as short as 50 ms. The new GPS sensor occupies about 1 cm³ (0.06 in³) and so can be included in the DTAG with little impact on size.

While the GPS-equipped DTAG is designed to provide accurate geo-referencing of the tagged whale at most surfacings, the position of the whale throughout long dives must be estimated by dead reckoning based on the inertial sensors in the tag. To improve the quality of the dead-reckoned track, we proposed to develop a miniature 3-axis speed sensor for the new tag. The initial sensor proposed used pulse-pair correlation of ultrasonic (1-2 MHz) pulses to determine speed in a manner similar to acoustic Doppler current profilers (ADCPs). New developments in gyroscope technology allowed us to replace this with a 3-axis low-power micro-gyroscope. The addition of the gyroscope signals allows orientation to be removed from the integrated acceleration signal, leaving speed as a result. As with the GPS, speed sensing (in the form of the gyroscope) adds little volume to the tag but will greatly improve the tracking accuracy of tagged whales.

The initial version of the tag had a limited recording duration and acoustic bandwidth making it most suitable for studying low frequency baleen whales (Johnson and Tyack 2003). An improved second version of the tag, funded by SERDP and completed in 2002, has enabled an increasing range of studies on odontocetes, especially deep-diving beaked whales. This version, called DTAG-2, is currently used in 10 or more field studies per year by researchers both at the Woods Hole Oceanographic Institution and from institutions around the world. The tag has been applied

to over 300 marine mammals from 13 species. Although a highly reliable design, the DTAG-2 requires considerable maintenance and no longer offers the best performance possible with today's semiconductor technology. The tag recording duration is limited to 12-18 hours and the recording bandwidth of 80 kHz does not sample the full bandwidth of vocalizations from phocoenids and many delphinid species. The tag is also limited in that it does not provide accurate positioning of the tagged whale as required for some studies. For this project, we proposed modifications to produce a new DTAG-3 better suited to observational studies of effects of sound.

Materials and Methods

Field Work at AUTEC

Both of the first two objectives:

1. Work with NUWC to locate beaked and other whales, tag them, and compare tag data on vocalizations with detections on range hydrophones to estimate probability of detection as a function of range and orientation of the tagged whale.

and

2. Develop methods and conduct studies on the effect of sonar and other sounds on beaked and other whales:

demanded work at the AUTEC naval underwater range. Much of the field work for SERDP 1539 took place in the TOTO and at AUTEC on Andros Island, Bahamas during August and September 2007 & August to October 2008 (Figure 1).

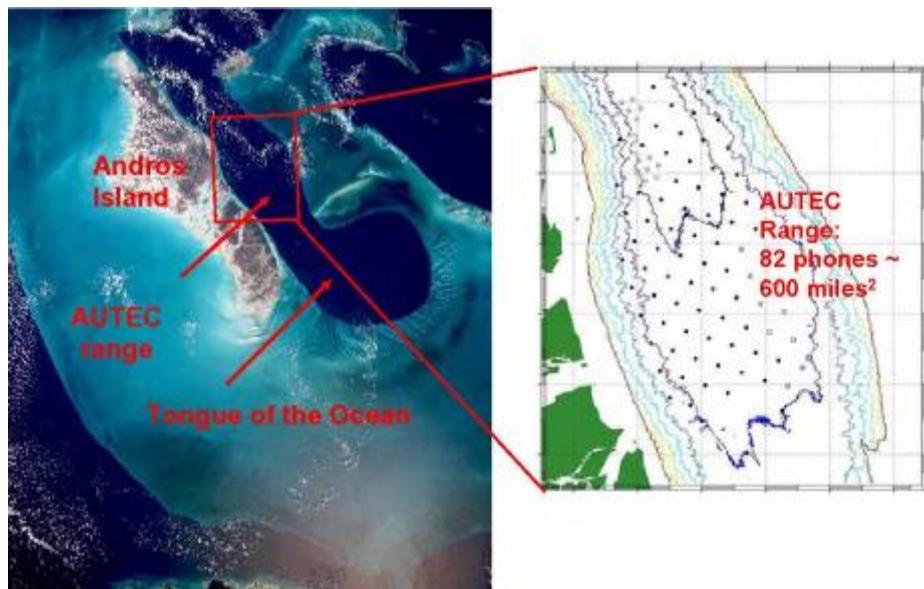


Figure 1. A Google Earth image of the southern Bahamas showing Andros Island and the Tongue of the Ocean, a canyon surrounded by shallow reefs in which the AUTEC Range is located. The range is shown in the diagram in the right. There is a 2m spacing between the hydrophones which are shown as circles or solid dots.

The field site selected for this project was in the Tongue of the Ocean, a basin of deep water to the east of Andros Island in the Bahamas which is surrounded by islands and sand banks. The only deepwater entrance to the basin is to the north. Three different species of beaked whale are sighted in Bahamian waters including the Tongue of the Ocean (Claridge, 2006). Blainville's beaked whales (*Mesoplodon densirostris*) are the most common, but Cuvier's beaked whale (*Ziphius cavirostris*), and Gervais' beaked whale, (*Mesoplodon europaeus*), have also been

sighted there (Claridge, 2006, Gillespie et al. 2009). The resighting rate of Blainville's beaked whales identified from photographs of natural markings indicates a relatively high rate of resight, but there has also been a consistent discovery of new animals over several years (Claridge, 2006, Boyd et al. 2007). These results suggest that at least some of the whales are resident, but that other individuals continue to enter or pass through the area. Several times a month, the AUTEC range hosts naval activities that make sounds including the propulsion noise of ships, acoustic pingers and a variety of sonars, but currently multi-ship mid-frequency tactical sonar exercises are only conducted about twice a year at AUTEC. Any resident animals would routinely hear anthropogenic sounds from naval activities on the range. No strandings have been associated with these exercises, making AUTEC a relatively low-risk site for initial studies on responses of beaked and other whales to sonar and other sounds.

Passive Acoustic Monitoring System for AUTEC hydrophone arrays

This site was selected not only because of the presence of beaked whales but also because of the demonstrated capability to detect and locate beaked whales acoustically by listening to an array of hydrophones installed by the U.S. Navy as part of its Atlantic Undersea Test and Evaluation Center (AUTEC), which is an underwater acoustic range (DiMarzio et al. 2008). AUTEC has a permanent grid of seafloor hydrophones covering about 600-square-miles in the deep ocean canyon of the TOTO where beaked whales are known to occur. The AUTEC range has 82 hydrophones that are mounted on the seafloor at depths of ≤ 2000 m and are cabled back to a building on shore. The U.S. Navy installed the array of hydrophones to track pingers attached to different vessels, and to monitor military exercises, but the hydrophones have also been used to detect and locate marine mammals, including beaked whales (DiMarzio et al. 2008). These hydrophones have a high enough upper frequency and close enough spacing to be suitable for tracking echolocation clicks of Blainville's beaked whales, which have a center frequency of about 40 kHz (Johnson et al. 2006). Signals from each of the AUTEC hydrophones can be recorded for later analysis, but are also displayed for real-time monitoring that can be used to help direct research vessels to the location of the whales (DiMarzio et al. 2008) and also to monitor positions and vocal behavior of whales before, during, and after naval sonar exercises.

Acoustic monitoring and tag data have shown that Blainville's and Cuvier's beaked whales make foraging dives about once every two hours (Tyack et al. 2006a, DiMarzio et al. 2008). The whales produce echolocation clicks for about 30 min while foraging at depth during each foraging dive. The source level of Cuvier's beaked whale is about 214 dB re 1 μ Pa at 1 m (Zimmer et al. 2005). Blainville's beaked whales are somewhat smaller than Cuvier's, and are thought to have a somewhat lower source level, perhaps 200-210 dB re 1 μ Pa at 1 m. The echolocation clicks of Blainville's beaked whales have a relatively narrow beamwidth, probably comparable to the 6 degree -3dB beamwidth of Cuvier's beaked whales (Zimmer et al. 2005, Ward et al. 2008). The range hydrophones tend to detect short series of echolocation clicks as a whale scans its beam past a hydrophone, although longer series can be recorded when the whales are close enough for off-axis clicks to be detected.

Beaked whale clicks can be detected on AUTEC hydrophones at ranges of up to 6500 m, usually when the whale is pointing within 30 degrees of the hydrophone (Ward et al. 2008). The typical separation of hydrophones is ~4km, so at least some clicks should be recorded from every deep foraging dive. When a group of beaked whales starts echolocating during a deep foraging dive,

these sequences of clicks are detected off and on at a few neighboring hydrophones for periods of typically tens of minutes (DiMarzio et al. 2008). We defined a group clicking period (GCP) as the time when sequences of clicks corresponding to one group foraging dive were detected on a cluster of nearby hydrophones. The start of a GCP was considered to be the occurrence of five or more distinct clicks typical of Blainville's beaked whale (known as a "click train") within a 30-second time interval. The end of the vocal period was considered to occur 30 seconds after the last distinct click train. Several different groups of beaked whales can be detected on the range simultaneously, with their clicks being detected by different groups of hydrophones at different locations on the range (DiMarzio et al. 2008).

Acoustic Recording Tag

The project also relies upon a digital archival, multisensor tag called a DTAG-2, that records animal sounds at sample rates up to 192 kHz (acoustic data sampled at 192 kHz) in concert with logging of depth, orientation and acceleration of the animal (Johnson and Tyack, 2003) (Figure 2B&C). An acoustic calibration of the tags was carried out at the Naval Undersea Warfare Center in Newport RI at pressures of up to 5.5 MPa (800 psi, equivalent to a hydrostatic pressure of about 550 m depth) showing that pressure had little effect on hydrophone sensitivity. The acoustic data from the tag were compared to records of detections on the range hydrophones. For clicks that could be detected on several hydrophones, the location of the clicking whale could be calculated based upon the time of travel from the whale to each hydrophone (Ward et al. 2008). These calculated locations were augmented where possible by visual observations of the surfacing tagged whale. The tag includes a VHF radio transmitter that facilitates tracking and resighting of the tagged whale. The tags were deployed for up to 18 hours on each whale using a suction cup attachment (Johnson and Tyack 2003). Tags were released after a preset time if they had not already released incidentally due to the movement of the animal or interaction with others.

The non-invasive DTAG is placed on an animal with the aid of a tagging pole and suction cups (Figure 2A&D) to provide acoustic and behavioral data from the tagged animal, environmental and anthropogenic sounds received by the animal, and sounds from vocalizing conspecifics.



Figure 2. (A) Tagging of a Blainville's beaked whale in the TOTO, (B & C) DTAG-2 Components, (D) Complete DTAG-2 with housing and suction cups.

Playback Experiments

A Behavioral Response Study (BRS) was conducted at AUTEC to study the responses of beaked and other whales to sonar and other sounds. The BRS experiments at AUTEC played the simulated sounds of MFA sonar, killer whales, and a Pseudorandom Noise (PRN) stimulus with the same timing and overall bandwidth as MFA to a sample of animals being monitored using the following methods: direct visual observation of the whales when at the surface, passive acoustic monitoring of whales when they were acoustically active (for beaked whales this was during deep foraging dives), and detailed behavioral and acoustic observations from DTAG-2s attached directly on focal individuals. Several different MFA signals were selected as stimuli, each with its own matching PRN stimulus. The “dose-escalation” experimental design involves controlling the level of exposure at the animal, and determining the minimum sound level that starts to elicit a response. The protocol achieves this goal by slowly increasing the received level at the whale from a level near what is just detectable until the whale responds, or a maximum planned level is reached. This ensures that the exposure at each whale is the minimum required to define the dose:response relation and to measure the response. Received levels of sound at the animal were always kept well below the level expected to cause temporary threshold shift and the maximum level allowed under our permits.

Many experimental designs require control subjects in addition to subjects expected to show a particular response. Observation of animals within the AUTEC range but not exposed to the BRS source transmissions provides baseline data on animals that are not hearing the transmissions. This establishes baseline behavior and can help rule out some undetected environmental factors that might be affecting the behavior of animals over the range during the period of the experimental exposures. Behavior often varies between individuals, so it is often useful to establish a within-individual control condition. The BRS experiments sampled one or more dives before exposure and as many dives as possible after exposure in order to establish within-individual baseline observations. Another critical control for the hypothesis that beaked whales are especially sensitive to MFA sonar involves testing other species. The first priority for this experiment was beaked whales, but when conditions were not good for tagging beaked whales, the protocol called for selecting other large deep-diving odontocete species to tag and test. High priority alternates included pilot and melon-headed whales, species that can be tagged relatively easily with the DTAG-2 and for which strandings have coincided with sonar exercises (Hohn et al 2006, Southall et al 2006). The goal was that, at the end of the entire research program, beaked whales would have been tagged and exposed in a variety of circumstances, and in addition there would be a similar number of exposures with the other species. Table 3 shows that even though the priority was to work with beaked whales and more time was spent attempting to tag them, these species are so difficult, that more tags were attached to other species and more CEEs were conducted with other species.

The first priority for the exposures was to define how beaked whales respond to MFA sonar sounds, with the goal of finding a safe indicator response for risk of stranding should the response intensify or be prolonged. While MFA sonar was the primary stimulus of interest, other stimuli were also used to test hypotheses about how specific the response to sonar was to the transmitted waveform. One standard “silent” negative control stimulus would involve the source ship doing everything it does for playback, except that it would not transmit a signal.

However, since the ship was stationary at the time of playback, and we could not control for other ships in the area, we did not use this no-playback ship-present control. There are also questions about how specific any observed response might be to MFA sonar signals. This would suggest broadcasting a negative control “noise” stimulus with the same timing and frequency range as the sonar stimulus, but with band-limited noise instead of the specific sonar waveforms. For this first phase of BRS, the judgment was made that this alternate PRN signal was more important than a no-playback control in which the ship did everything but play back the signal. One important reason for this was that the initial playbacks involve a stationary source and ship, with no ship propulsion noise. The control approach would be more important if the CEE involved a realistic approach with a moving source vessel.

One hypothesis for the link between sonar exposure and strandings proposes that while MFA sonar signals are an order of magnitude lower in frequency than the best hearing of beaked whales (Cook et al. 2006, Finneran et al. 2008) and the center frequency of beaked whales’ own sounds (Zimmer et al., 2005; Johnson et al., 2006), and are quite different in structure from beaked whale clicks, the sonar signals are quite similar to killer whale (*Orcinus orca*) sounds (Ford, 1991). If beaked whales have an intense avoidance reaction to MFA sonar signals, this might be explained as an anti-predator reaction, indicating that beaked whales interpret MFA sonar signals in error as the calls of killer whales, a known predator (Zimmer and Tyack 2007). Testing this hypothesis requires playing back the natural sound of killer whale calls as a positive control stimulus.

For the first set of experiments in BRS07, we used a silent condition as a pre-exposure baseline, MFA playback for the primary experimental stimulus, and killer whale calls as a positive control. The basic protocol for each experiment called for the subject to be tagged. Baseline data were collected for one pre-exposure foraging dive. At the start of the next foraging dive, the source vessel positioned itself for playback of the first stimulus, which commenced once the acoustic monitors heard the onset of echolocation clicks. The source level was slowly ramped up, increasing exposure level at the whale until clicking was heard to stop or a maximum level was reached. Sound exposure ceased as soon as the animal was confirmed to have stopped clicking or after a pre-selected duration at the maximum source level. Once the third foraging dive started and acoustic monitors again heard echolocation clicks, the second stimulus was played back with a similar ramp up procedure. This second playback also ceased once clicking was confirmed to have stopped. In 2008 a similar protocol was used, except it involved two pre-exposure dives. The remaining duration the tag was on was used as post-exposure control. This design was used to optimize the ability to compare responsiveness of the same individual in a similar behavioral state to the two different stimuli presented.

Mitigation and monitoring observations, both vessel-based and aerial, were conducted at the start and end of the BRS field effort and after both beaked whale playbacks to ensure that there were no injured or stranded marine mammals in and around a large area surrounding the location of each playback. In some cases, weather and practical considerations extended the periods of time over which this monitoring was conducted, but for all playbacks there was extensive monitoring of both the waters and surrounding shorelines. No distressed, injured, or stranded animals were detected at any time.

Tag Development

The new DTAG-3 developed for this project was designed using a combination of simulation, computer-aided design, and rapid sub-system prototyping. Steps taken to address the specific design goals are described below.

Reduced tag volume

Reducing the volume and flow cross-section of the tag are essential to obtain longer duration attachments, to lower the impact of the tag on the animal, and to improve data quality. A smaller tag is also needed to study many delphinids for which the current tag is simply too large. The target 50% reduction in volume required a substantial miniaturization of the electronics and more efficient packaging. To this end, we replaced the three layers of plastic comprising the DTAG-2 housing with a single integrated plastic housing and the tag electronics have been reduced to a stack of two circuit boards equal in size to the rechargeable battery. The complete electronics package for the DTAG-3 succeeded in reducing to 50% of the volume of that in DTAG-2. Choosing lightweight circuit boards, components and batteries led to an approximate 40% reduction in weight, which reduces the volume of syntactic foam flotation needed in the tag.

In tandem with the reduction in tag size, we reduced the diameter and height of the suction cups by 25%. This reduction reduces the attachment force of the cups by 25% compared to DTAG-2 for a given level of vacuum but the drag force experienced by the new tag, which is proportional to flow cross-section, should be 60% less than for DTAG-2, suggesting that the smaller cups should be more, rather than less, tenacious. Although suction cup performance is not currently the primary factor limiting recording duration in DTAG-2 (attachments of 3 days have been obtained on a few occasions when the release mechanism has failed), we have worked to pinpoint the reasons for eventual suction cup failure to improve reliability in multi-day deployments. After eliminating a number of failure modes, we have focused on creep in the suction cup material and in the biological substrate (i.e., the epidermis) as being the most likely reason for detachment. Remnant air in suction cups leads to very high vacuum forces when the host animal dives to depths beyond 100m. These forces translate into high shearing forces in the skin tissue as skin is drawn into the cup. We have a new NOPP grant to study factors limiting duration of attachment of non-invasive tags, and we are continuing to explore whether changes in the suction cup lip will reduce skin shearing and so minimize creep.

Longer recording duration

A recording duration of 48 hours for mid-frequency animals such as beaked whales and 5 days for low frequency (baleen and sperm) whales can be obtained using 16 GBytes of FLASH (solid-state) memory. This is about double the memory of DTAG-2 but, due to newer high-density memory components, can be implemented in a smaller volume. Extending the recording bandwidth of the tag to accommodate delphinid vocalizations was also straightforward with off-the-shelf components. However, the volumetric capacity of batteries has changed very little since the design of DTAG-2 and power consumption is thus now the limiting factor in an acoustic recording tag. Achieving the target recording duration required that power consumption be reduced to 30% of that of DTAG-2. This necessitated the use of a more efficient digital signal processor (DSP, the microprocessor used in the tag) and careful reduction in the power consumption of each sensor. The change of DSP is significant because much of the time-critical

code in DTAG-2 is written in a platform-specific assembly language and had to be completely re-written for the new processor. Serendipitously, the tag group at WHOI has been working simultaneously on two other development projects that required much of the same software as did the new tag. The projects, a diver-worn acoustic dosimeter funded by the Navy Submarine Medical Research Lab and a self-contained underwater acoustic detector funded by ONR, provided an opportunity to spread the development cost and risk of the new tag software and hardware. The dosimeter, in particular, was in many respects a reduced-size prototype of the new tag without the navigation sensors.

Geo-positioning and physiological sensors

The sensor suite in DTAG-2 provides information about the relative movements of the tagged animal but the long-term positioning accuracy is poor due to the open-ended accumulation of errors. The new DTAG-3 design incorporates a GPS sensor to provide precise positions of the animal at each surfacing. A lock-less GPS acquisition technique has been developed to allow positioning from sub-second surfacing durations. This method relies on post-processing with web-published orbitology information to produce position fixes from as little as 50 msec of satellite data. Because the high frequencies used by GPS do not pass through water, it is essential that the plastic surface of the tag above the GPS antenna shed water rapidly and we have experimented with hydrophobic coatings to improve shedding. This is the one area of the SERDP project that where the objectives have not fully been met. The GPS sensor is functional but still requires some additional evaluation and fine-tuning.

In addition to the GPS sensor, information about the three-dimensional velocity of the tagged whale is needed to estimate position between surfacings. In the proposal, we envisioned using a three-axis acoustic Doppler velocity sensor to obtain this data. However, the recent availability of miniature low-power gyroscopes, in combination with the existing inertial sensor suite in the tag, offers another speed sensing approach that is more volumetrically efficient. The power consumption of the gyroscope has been offset by reducing the power consumed by another sensor, the magnetometer, which is used to determine the heading of the animal. The power consumption of this device has been reduced by a factor of 3, at the expense of a small increase in sensor noise, by using a multiplexing technique.

An electrocardiogram (ECG) sensor is of great interest in studying diving, energetics, and startle responses to acoustic disturbances (Götz 2008). However, cardiographic sensing on a free-swimming animal is complicated by the small separation of the sensing electrodes relative to the distance between sensor and heart, and by interference from myo-electric signals generated by the large swimming muscles. The new tag incorporates a novel multi-channel low-noise ECG sensor that may overcome these problems. Each of the 4 suction cups contains an electrode and these are combined diagonally to produce 2 differential channels. Myo-electric noise is reduced by filtering and beamforming these channels in post-processing.

High reliability radio beacon

The most frequent maintenance task for DTAG-2 involves swapping the battery in the radio beacon used to locate the tag. In the DTAG-2 design, the battery in the radio transmitter was kept separate from the main tag battery to ensure continued operation of the beacon even in the event that the tag electronics failed. In the new design, the radio transmitter is built onto the main

circuit board and powered from the main battery. The rate of radio transmissions reduces from 1 per second to 1 per 5 seconds as the batteries discharge to maximize lifetime. To ensure confidence with this critical sub-system, the transmitter circuit is identical to that used successfully throughout the DTAG project. The circuit is now integrated into the DTAG-3 under a collaborative agreement with the transmitter designer, Advanced Telemetry Systems. Integrating the transmitter reduces the parts count and the amount of servicing required without compromising the detection range or longevity of the transmitter. In addition, having the VHF circuit inside the DTAG allows it to be program controlled. To save power the transmitter can be turned off whenever the DTAG is under water and transmit at a much lower rate when off the animal, floating at the surface, waiting to be recovered; it can also transmit more frequently when on animal at the surface to allow better tracking.

Results and Discussion

The presentation of results and discussion is divided into the following three basic objectives of this project:

1. Work with NUWC to locate beaked and other whales, tag them, and compare tag data on vocalizations with detections on range hydrophones to estimate probability of detection as a function of range and orientation of the tagged whale.
2. Develop methods and conduct studies on the effect of sonar and other sounds on beaked and other whales.
3. Develop tagging techniques and field efforts to enable observational techniques or experiments that use the tag to monitor reactions of marine mammals to exposures of manmade noise. We proposed to complete the development, bench testing, and field evaluation of the new tag design and to build a quantity of tags for field evaluation.

1. Validate Passive Acoustic Monitoring and Estimate Probability of Detection as $f(\text{range}, \text{animal orientation with respect to sensor})$

The initial plan for validating passive acoustic monitoring for this project is illustrated in figure 3.

Validate Probability of Detection for Passive Acoustic Monitoring

Analyze Probability of Detecting Whale Clicks
Whale makes a foraging dive every 3 hours
4000 clicks/foraging dive

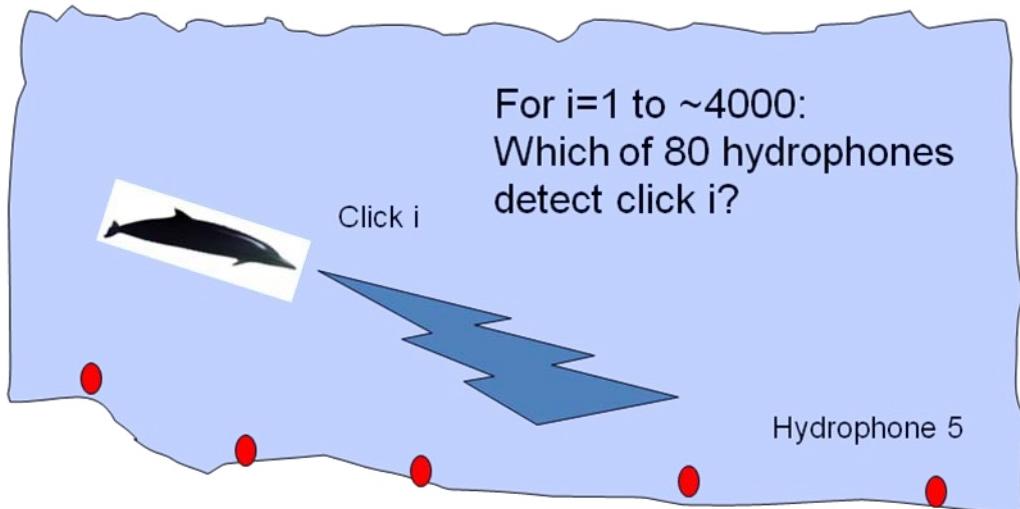


Figure 3. Scheme for estimating probability of detection as $f(\text{range}, \text{animal orientation with respect to sensor})$.

Localization of tagged beaked whale and estimation of detection function

The method for achieving this objective involved Dtagging a beaked whale and then listening for its clicks on the AUTEC array of hydrophones. The first DTAG data set used for this goal came from a probable female *M. densirostris* that was tagged in a group believed to consist of two mother-juvenile pairs at 11:37:38 a.m. (+/- 5 seconds) local time on October 23, 2006 as part of our SERDP sponsored tagging research. The GPS location recorded for the tagging was 24° 30.412' N, 77° 35.320'. Clicks recorded on the DTAG were classified as belonging to the tagged whale based on two features. The attachment of the tag to the whale results in a low-frequency energy component that is not present in clicks from conspecific whales (Zimmer et al. 2005). Second, the angle of arrival for clicks from the tagged whale is close to zero between the two hydrophones on the tag, while for clicks from conspecifics it varies as the whale moves with respect to the tag hydrophones (Johnson et al. 2006). While the DTAG recorded clicks from this whale, acoustic data from all of the AUTEC hydrophones were also recorded by NUWC personnel at a sample rate of 96 ksamples/sec. NUWC personnel developed a matched filter to detect clicks of beaked whales from the range hydrophones, using a high SNR click from a *M. densirostris* as per Ward et al (2008). Each beaked whale emits a series of clicks with unique inter-click-interval timings. This allowed NUWC personnel to find on AUTEC hydrophones clicks from the tagged whale by listening for the same interclick interval (ICI) pattern that was recorded on the DTAG.

While Ward et al. (2008) detected many thousands of clicks from the tagged beaked whale (92% of all clicks) on at least one AUTEC hydrophone, only 1% were detected on four or more hydrophones, the number required for localization. Figure 4 shows the original track derived from the DTAG and the corrected track derived from the 577 acoustic locations made using the AUTEC array. Figure 5 relates an enlarged plot of the corrected track to each acoustic location derived from the AUTEC array.

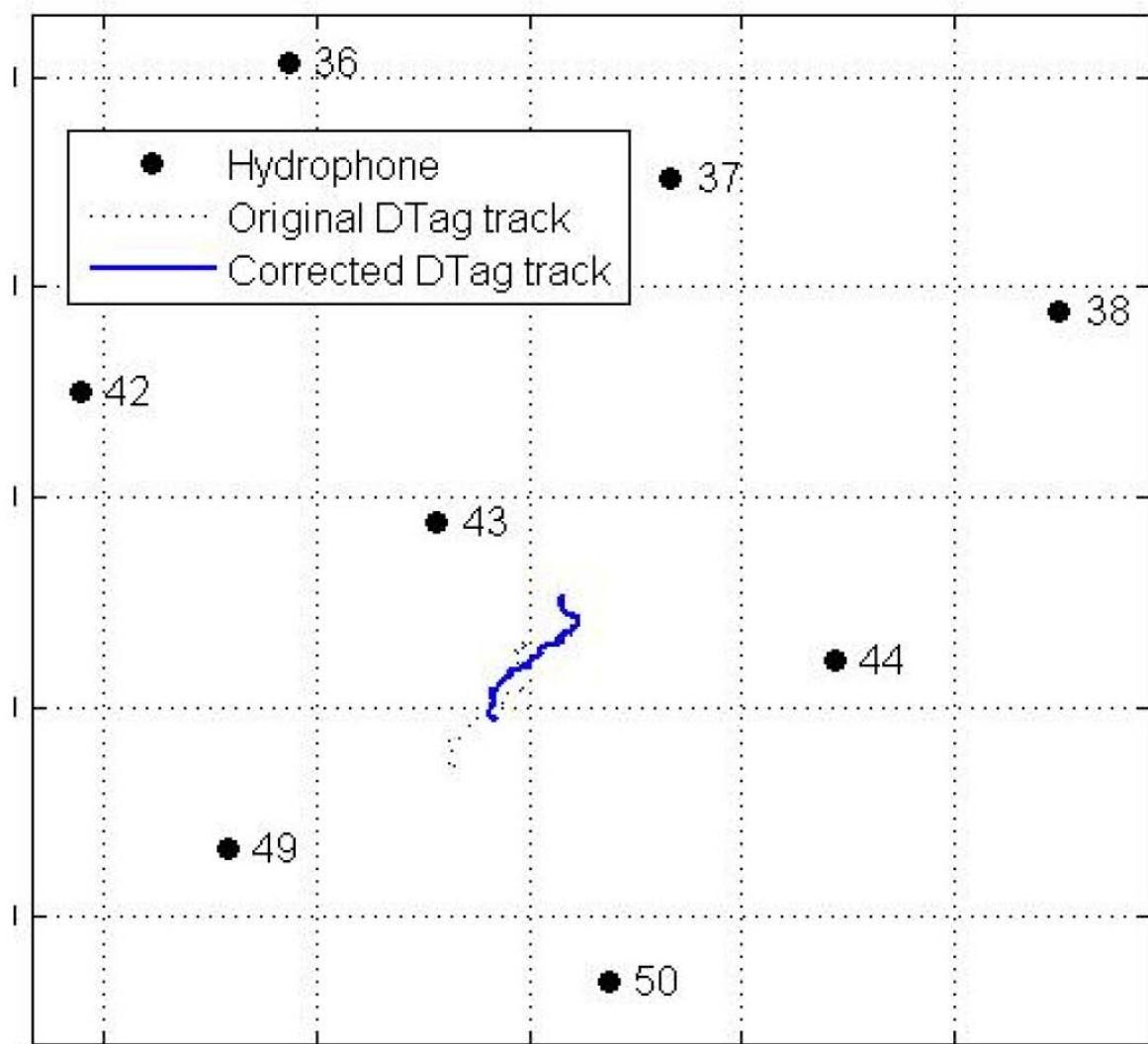


Figure 4. Track of tagged whale Md07245a georeferenced by acoustic location of clicks. The original DTAG Kalman-filtered track indicated by dots and corrected DTAG track in blue, each grid square is 2 km x 2 km. Figure reproduced from Ward et al. 2008.

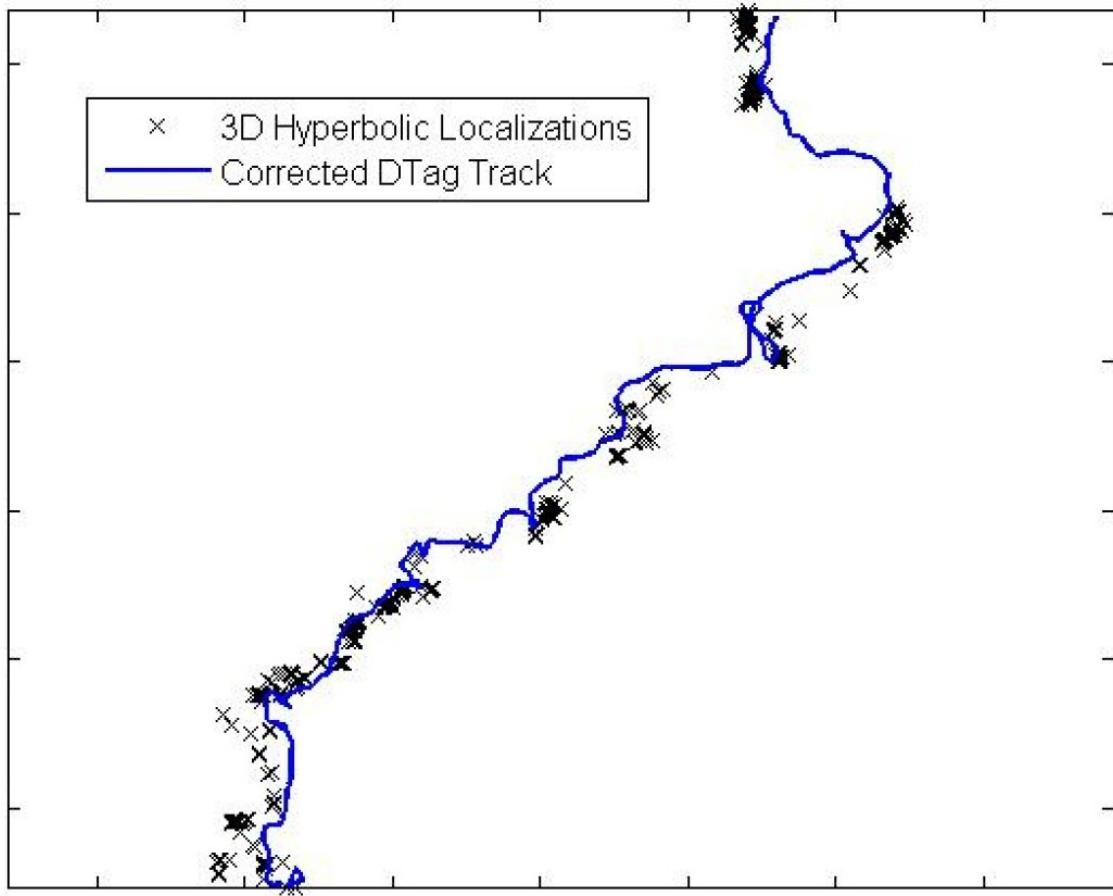


Figure 5. Track of Tagged whale Md07245a georeferenced by acoustic location of clicks. DTAG track corrected based on 3D hyperbolic localizations, tick marks at 200-m increments. Figure reproduced from Ward et al. 2008.

Ward et al. (2008) summarized how the probability of detecting clicks varied as a function of range and aspect: “The 3D localizations created using the matched filter detection data were used to determine the range from the whale to the hydrophone for each detection method. Clicks from each hydrophone determined to be valid on the basis of their TDOA (time difference of arrivals) with the DTAG were used to estimate range and bearing to each hydrophone. The maximum detection range for both methods was approximately 6500 m, significantly greater than previously estimated (Tyack et al. 2006b). The whale was traveling generally in a north-east direction, but was observed to turn at various times in all directions. The off-axis aspect angle between the caudal-rostral axis of the tagged whale and the receiving hydrophone was determined by subtracting the bearing angle from the whale to the hydrophone from the heading measured by the DTAG. The detection range as a function of off-axis aspect angle is depicted in figure 6. The majority of the clicks detected at far ranges were within ± 30 degrees. With decreasing range, a greater number of clicks were detected further off-axis. While a -3 dB beam width of 6° has been suggested for *Z. cavirostris* by Zimmer et al. (2005), *M. densirostris* may be less directional due to their smaller body size and potentially smaller source aperture (Tyack et al. 2006b).”

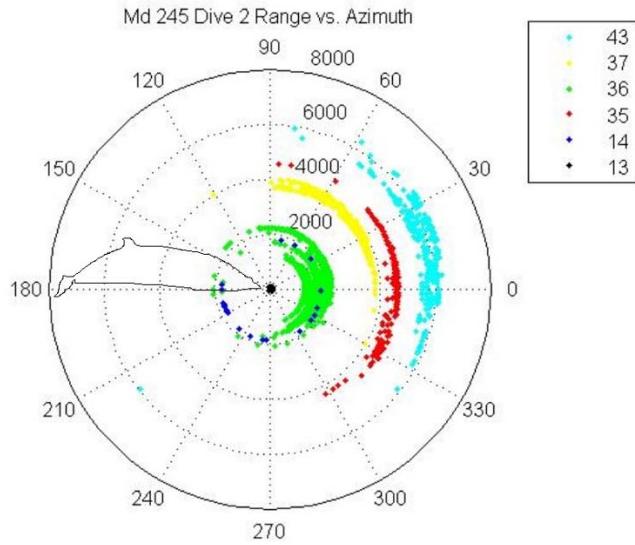


Figure 6. Plot of Range vs Azimuth of clicks produced by tagged whale Md07245a as recorded by AUTEC hydrophones. The hydrophone source of each point is indicated by the color scheme marked on the legend. Figure reproduced from Ward et al. 2008.

Estimating the beampattern of Mesoplodon densirostris

Once the detections of clicks could be expressed as a function of range and aspect, Ward et al. at NUWC were able to estimate the beam pattern of the tagged whale. Using the calibrated received level of the click as measured on the AUTEC hydrophone and estimating transmission loss as 20 log range, it was possible to estimate the source level for each click as a function of angle measured between the orientation from the clicking whale's body axis and the bearing from the whale to the hydrophone on which the click was recorded. This yielded the mean and maximum beampatterns shown in figure 7.

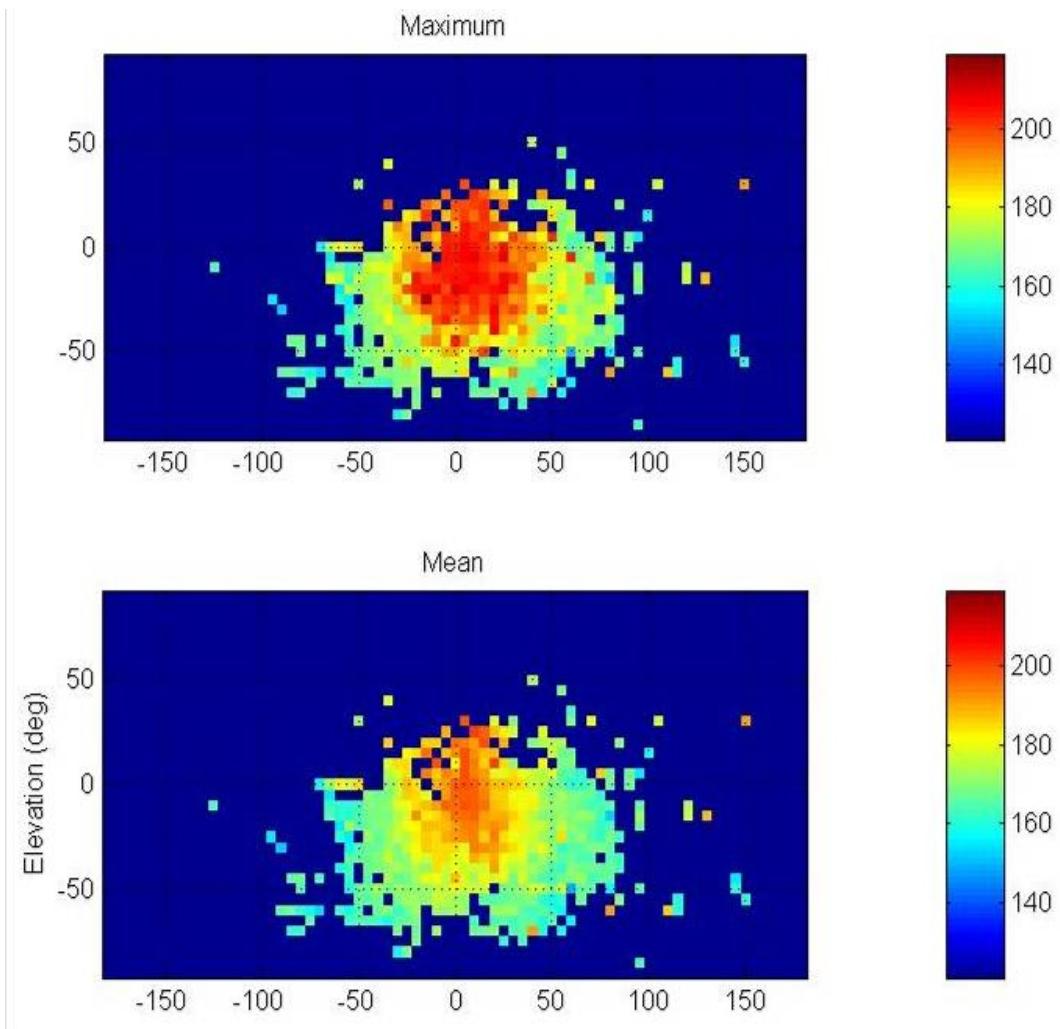


Figure 7. Beam pattern of tagged whale Md07245a measured using the range and orientation of the tagged whale with respect to the hydrophone. Courtesy of J. Ward NUWC NPT.

*Probability of detecting Blainville's beaked whales, *Mesoplodon densirostris*, as a function of range*

A larger data set from 5 Blainville's beaked whales, *Mesoplodon densirostris*, or Md, tagged at AUTEC were used to estimate the probability of detection as a function of range (Table 1).

Table 1. Tag ID, date the animal was tagged, number of dives while animal was tagged, and number of dives with data available for estimating the detection function $g(y)$ (from Marques et al. 2009).

Tag	Date	Number of Dives	Dives for $g(y)$
Md296	23 Oct 2006	3	3
Md227	15 Aug 2007	6	0
Md245	2 Sep 2007	4	3
Md248a	5 Sep 2007	4	4
Md248b	5 Sep 2007	4	3
Total		21	13

Marques et al. (2009) were able to achieve precisely the measurement objective of this part of the SERDP project using SERDP tag data: “For the estimation of the detection function, further data processing was required. For four whales and a total of 13 of the deep dives, these DTAG data were associated with matched filter detections from the surrounding hydrophones, localized, and the pseudotrack georeferenced (i.e., absolute rather than relative coordinates obtained; see Ward et al., 2008 for further details). Once georeferenced, the DTAG accelerometer and magnetometer data for each click within the georeferenced portion of the dive were used to calculate the spatial relationship between the whale and each hydrophone in the whale orientation frame (see Johnson and Tyack, 2003; Ward et al., 2008, for further details). An indicator of detection (1—detected; 0—not detected) could then be generated for each click produced at each surrounding hydrophone, as well as a set of corresponding click characteristics in the frame of the whale (namely, slant distance, vertical, and horizontal off-axis angles with respect to the whale’s orientation).”

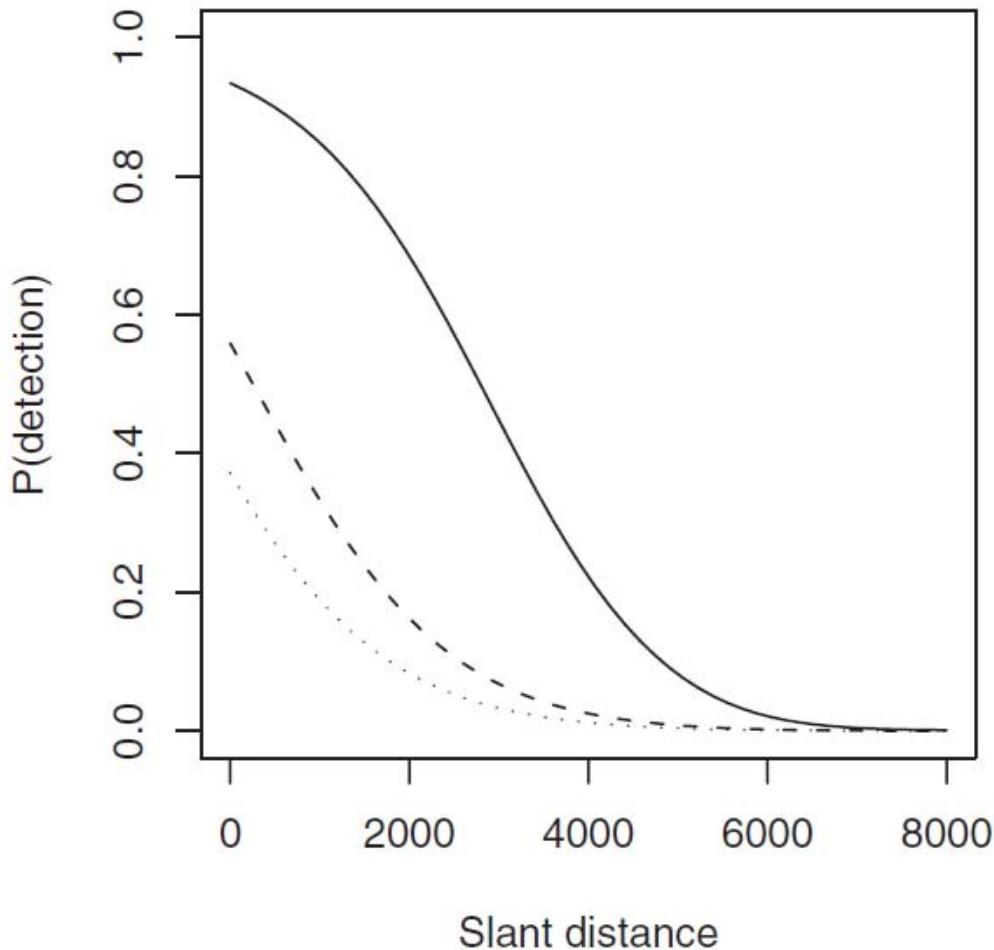
The DTAG data were then used to simulate the movement typical of beaked whales diving on the range. The DTAG data were also used to estimate the click production rate per whale judged from the start of one deep foraging dive to the start of the next one. The density (D) of whales judged from the number of clicks detected over time period T was estimated using the following equation

$$D = \frac{n_c (1 - \hat{c})}{K\pi w^2 P^\wedge T r^\wedge} \quad (1)$$

where w is the distance away from the hydrophones beyond which cues are assumed to not be detected, P^\wedge is the estimated average probability of detecting a cue made within distance w , r^\wedge is the estimated cue production rate, \hat{c} is the estimated proportion of false positive detections, and K is the number of replicate sensors used. The estimated click rate was 0.407 clicks/second, with a standard error of 0.040, resulting in a CV of 9.8%. Overall, of the 160,302 sounds detected and

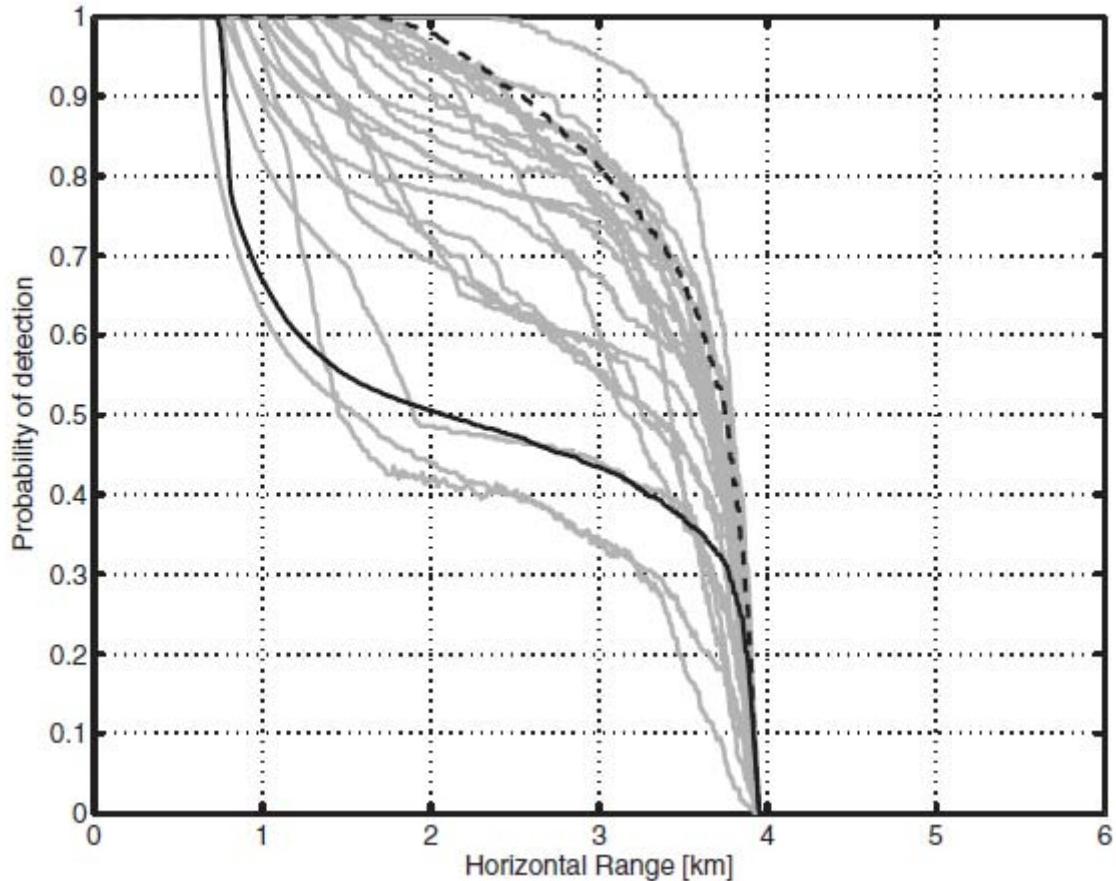
considered to be beaked whale clicks during the sample periods used for the false positive proportion estimation, only 78,450 corresponding to slightly under 50% were unambiguously identified as Md clicks. The complement of the proportion of false positives, $1-c^*$, was estimated to be 0.549 ($se=0.011$, $CV=1.99\%$) or 0.489 ($se=0.011$, $CV=2.29\%$), depending on whether the mixed clicks are considered to be all or none from Md.

The estimated detection function is shown in figure 8. The maximum distance at which a click was detected was 6504 m. The estimated mean detection probability for clicks produced within 8 km of the hydrophones (clicks outside this buffer are assumed to have 0 detection probability) was 0.032, with an associated CV of 15.9%. Using Eq. 1 the estimated Md density at AUTEC over the recording period was 25.3 or 22.5 animals per 1000 km^2 (with respectively 19.5% and 19.6% CV 's), depending on the value for \hat{c} used. Assuming a log-normal distribution for the density estimate, the respective 95% confidence intervals for density are 17.3–36.9 and 15.4–32.9.



*Figure 8. The estimated detection function for *Mesoplodon densirostris* echolocation clicks detected at AUTEC. The off-axis angles are fixed at 0, 45, and 90° respectively by the solid, dashed, and dotted lines. Figure reproduced from Marques et al. 2009.*

This detection function was based upon a statistical model. Zimmer et al. (2008) used data from SERDP supported tagging of *Ziphius cavirostris* in the Ligurian Sea to take a more acoustics-based approach to the detection function for *Ziphius*. Knowledge about the beam pattern of beaked whales is particularly important for this approach. Note that the Marques et al. (2009) detection function has around 50% detection at 45 or 90 degree off-axis angles even for ranges very near the whale. By contrast, the Zimmer et al. (2008) detection function (Figure 9) has 100% probability of detection out to a range of about 700 m, independent of off-axis angle.



*Figure 9. Detection functions for a beaked whale echolocating at a depth of 720 m with a receiver depth of 100 m. The solid black curve corresponds to a simple simulation with normally distributed heading, pitch, and elevation. The gray lines show the probability of detection for clicks generated during 23 measured dives made by six Cuvier's beaked whale, *Ziphius cavirostris*. The dashed black curve shows the effect of allowing a simulated whale to reverse the direction of its travel periodically. Figure reproduced from Zimmer et al. 2008.*

These final statistical estimates of density of *Mesoplodon densirostris* at AUTEC extend beyond the SERDP objectives, and while using SERDP data, were funded as part of the DECAF project (<http://www.creem.st-and.ac.uk/decaf/>), but they show the remarkable progress that this SERDP project has enabled for PAM applications that are significant for basic ecological research and also for applied applications such as monitoring marine mammals on a navy range.

2. Behavioral Response Study: Develop methods and conduct studies on the effect of sonar and other sounds on beaked and other whales.

A top research priority identified by most reviews of the sonar-whale problem involves experiments to study how beaked whales respond to controlled exposures of sound. One of the biggest concerns about designing these experiments involved how difficult these animals are to monitor. The ability to monitor beaked whales with the AUTEC array of hydrophones coupled with the demonstrated capability of tagging beaked whales on the AUTEC range funded by SERDP in 2006 offered an exceptional opportunity for controlled exposure experiments. In the summers of 2007 and 2008 an international team of biologists, acousticians, and engineers converged on this range for a Behavioral Response Study designed to test how beaked and other whales respond to sonar and other sounds. The experiment compared responses of beaked whales to those of other toothed whale species to test for whether beaked whales are especially sensitive. The sound stimuli selected for the experiment were influenced by a puzzle and a hypothesis. The puzzle was the mismatch between the frequencies heard best by beaked whales (>40 kHz; Cook et al. 2006, Finneran et al. 2008) and the center frequency of beaked whales' own sounds (>24 kHz; Zimmer et al. 2005; Johnson et al. 2006) compared with the frequencies of the naval sonars involved in the strandings (<8 kHz; D'Amico et al. 2009). Most risk analyses would say that with such a large gap between the mid-frequencies of the sonar and the higher frequencies that whales use, there should be little risk of the sonar causing problems with the whales. Several different scientists puzzling over this problem noticed that while the naval sonar signals are very different from the clicks used by beaked whales, they are quite similar to the calls of killer whales, a dangerous predator of beaked whales. This led to the hypothesis that beaked whales might show a strong anti-predator response to the sonar signals (Zimmer and Tyack 2007). The stimuli selected to test this idea were an actual naval sonar signal, calls of marine mammal-eating killer whales, and a noise stimulus with the same overall frequency band and timing as the sonar signal, but with a waveform that sounded very different from either sonar or killer whale.

Table 2 lists the stimuli and subjects selected for the BRS AUTEC project.

Table 2. List of stimuli and subjects selected for the BRS AUTEC project.

- STIMULI
 - MFA: mid-freq active sonar (actual 53C waveform)
 - PRN: pseudorandom noise with same timing and overall bandwidth as MFA
 - ORCA: Calls of mammal-eating killer whales
- SUBJECTS
 - Blainville's beaked whale, *Mesoplodon densirostris*
 - Other toothed whales with sonar-related strandings: Pilot whales, Melon-headed whales
 - Other toothed whales with no sonar-related strandings: False killer whales

Design of BRS experiment

The design of the experiment called for tagging a beaked whale, collecting pre-exposure data during the first one or two foraging dives, then as soon as echolocation clicks were heard during the next foraging dive, for a ship to start playing back one of the stimuli at a level so low that the whale could not hear it, then increase the level regularly until it reached a maximum level (well under the level of the actual sonar) or the whale stopped clicking. Experiments to species other than beaked whales were designed to follow timing similar to that used with beaked whales in order to facilitate comparisons across taxa.

Data sampled for BRS07 and BRS08

Over the course of BRS07 and BRS08, data were collected from 18 tag deployments (Table 3), 7 on Blainville's beaked whales, *Mesoplodon densirostris*, 7 on pilot whales, *Globicephala macrorhynchus*, two on false killer whales, *Pseudorca crassidens*, and two on melon-headed whales, *Peponocephala electra*. A total of 137 hours of data were collected from tags, 78 hours from beaked whales, 43 hours from pilot whales, 11 hours from false killer whales, and three hours from melon-headed whales. The data collected by the tag included sounds produced by the tagged animal, environmental and anthropogenic sounds received by the animal, details of the animals movements in terms of its diving, swimming speeds, changes in orientation and swimming actions.

Table 3. Cetaceans tagged and CEEs conducted at AUTEC during BRS07 and BRS08.

Date	Species	Tag Info	Stimulus
15 Aug 07	Blainville's Beaked whale	1047-0615 On 19:28	baseline
17 Aug 07	Pilot Whale A	1304-0203 On: 12:59	MFA1 ORCA
17 Aug 07	Pilot Whale B	1415-1727 On: 03:13	MFA1 ORCA
23 Aug 07	Blainville's Beaked whale	1352-1455 On: 01:03	baseline
23 Aug 07	Blainville's Beaked whale	1401-1448 On: 0:58	baseline
2 Sep 07	Blainville's beaked whale	1004-0339 On: 17:35	MFA1 ORCA
5 Sep 07	Blainville's beaked whale	1044-0436 On: 17:52	Baseline
5 Sep 07	Blainville's beaked whale	1431-0800 On: 17:29	Baseline
16 Sep 07	Pilot Whale	1351-0642 On: 16:51	Baseline
16 Sep 07	Pilot Whale	1002-1119 On: 1:17	Baseline
22 Sep 08	Pilot Whale A	1027-1326 On: 2:59	Baseline
22 Sep 08	Pilot Whale B	1534-LOST	PRN1, MFA1
26 Sep 08	False killer whale	0821-1319 On: 4:58	PRN1 MFA1
27 Sep 08	Blainville's beaked whale	1117-1537 On: 4:20	PRN1
28 Sep 08	False killer whale	1703-2325 On: 6:22	MFA1 PRN1
29 Sep 08	Pilot Whale	1022-1641 On: 6:19	PRN1 MFA1
29 Sep 08	Melon-headed whale	0839-0854 On: 0:15	Baseline
29 Sep 08	Melon-headed whale	1333-1636 On: 3:03	PRN1 MFA1

Playbacks were performed on only 2 of the tagged beaked whales, on 2 Sept 2007 and 27 Sept 2008. This is a lower total than was anticipated. Long stretches of poor weather incompatible with tagging, and a series of severe storms during 2008, meant that effective tagging opportunities were greatly reduced. However, those playback experiments conducted did demonstrate that these methods could safely be used in these species using anthropogenic and biological sounds to generate very detailed information on received exposures and behavioral responses. A large enough set of baseline data were gathered on tagged *Mesoplodon densirostris* that the three playbacks to two whales were sufficient to define a statistically significant response to the sound playbacks. During the last week of BRS08 when the RV Revelle returned to AUTEC and found conditions suitable for tagging odontocetes, 1 beaked whale, 3 pilot whales, 2 false killer whales and 2 melon-headed whales were tagged, with 6 playbacks completed. This shows that while tagging beaked whales is very difficult, it is possible to obtain a good sample of playbacks from other species when the weather cooperates.

Photo-identification of beaked whales in the study region over several years before the study, as well as identification of animals during BRS07 and BRS08, suggests a degree of residency within the region, with some individuals seen over multiple years. On the other hand, the discovery curve of new individuals has not leveled off, suggesting some influx of new animals each year.

Playback of MFA and ORCA to Mesoplodon densirostris in 2007

The following is a summary of results from the playback to the beaked whale in 2007. After a pre-exposure dive, a MFA sonar playback was conducted on a tagged female adult *Mesoplodon densirostris*. The MFA playback started at a source level (SL) of 152 dB re 1 μ Pa at 1 m, a few minutes after the whale began producing ultrasonic clicks. The SL was then increased by 3 dB every 25 s in a ramp-up procedure, reaching a maximum SL of 212 dB re 1 μ Pa at 1 m after 9 minutes. The MFA signal was then played back at maximum SL every 25 sec for 6 minutes. The first ping detected on the tag and for which received level (RL) could be estimated, had an RL of ~95 dB re 1 μ Pa (Figure 10)

After 10 min into the playback, the whale appeared to stop clicking earlier than usual, when the RL at the whale was ~138 dB. The playback continued for several minutes once cessation of clicking was confirmed. The maximum RL recorded at the whale was ~147 dB. Because this dive was so short, she had an unusually low number of whale buzzes (very rapid series of clicks) which are indicative of foraging events. The whale then ascended more slowly than usual and, as a result, had a longer than normal ascent.

After the whale surfaced, her behavior appeared normal. After about 2 hours she started another deep foraging dive (Figure 10). Once she started clicking at depth, a playback of killer whale sounds was started. The killer whale playback started at an initial SL of 130-140 dB, a few minutes after the whale began producing ultrasonic clicks. The SL was then increased by about 5 dB about every 30 sec in a ramp-up procedure, reaching a maximum SL of 190-203 dB after 10 minutes. The killer whale playback was stopped several minutes after the whale stopped clicking, before the ramp up process had reached maximum SL.

The first killer whale sounds detected on the tag for which RL could be estimated had a peak RL of ~98 dB (Figure 10). The whale stopped clicking about 5 minutes into the killer whale playback, a shorter clicking period than usual. The received level of the killer whale sounds recorded on the tagged whale just before she ceased vocalizing was ~102 dB. The sound exposure at the whale continued for several minutes once the cessation of clicking was confirmed. The maximum RL recorded at the whale was ~126 dB. This exposure dive had the shortest overall clicking period, the lowest number of buzzes, the slowest ascent rate, and the longest ascent among the beaked whale deep foraging dives recorded at TOTO in BRS07 from 5 individual whales (Figure 10).

As soon as the killer whale playback stopped, the beaked whale started swimming away from the location of the sound source and she continued swimming on a much straighter course than usual, although she made two additional deep foraging dives during this movement, the first of which was 4.8 hours after the killer whale exposure dive. This inter-dive interval is longer than any of the other times between deep foraging dives of *Mesoplodon* recorded during the BRS at AUTEC. By the time the tag was released from the whale, 10 hours after the end of the dive that contained the last playback, the whale had traveled approximately 20 km (10.8 nm) from the playback location at an average horizontal speed of about 0.5 m/s (1 kt) (Figure 11). Note that the pseudotracks on Figure 11 are not fully georeferenced as were the track segments illustrated in Figure 5, so they should be taken more as an integrated view of changes in heading than as a geographically precise track.

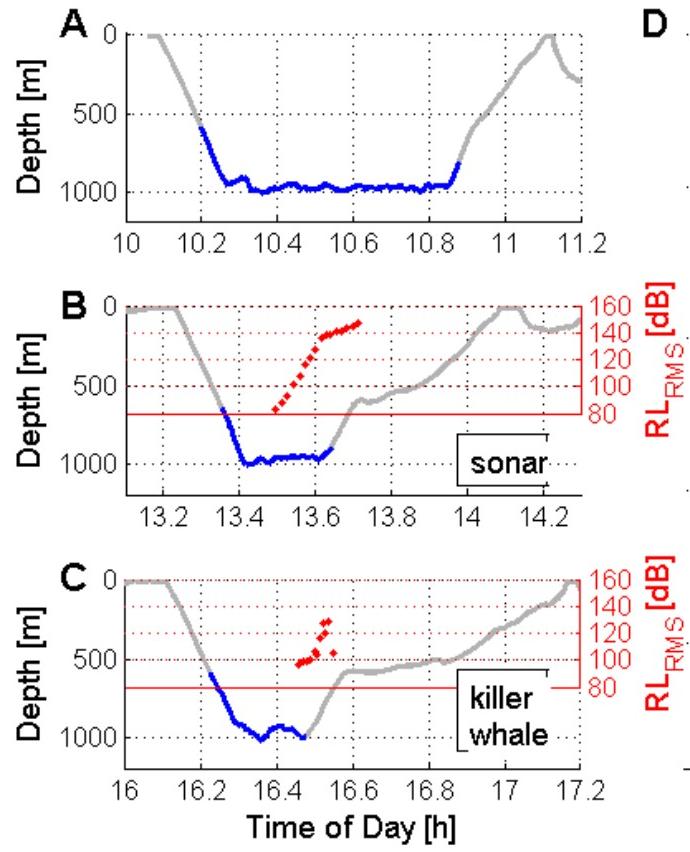


Figure 10. The first three dive profiles of the female beaked whale involved in the 2007 playback. The left hand axis shows the depth of the whale (gray:silent, blue:clicking) during the time that the tag was attached. During dive 2 she was exposed to a playback of MFA sonar and during dive 3 to killer whale sounds. Each of the red diamonds shows when the tag on the whale received playback sound and the received sound level (dB_{rms} re $1 \mu\text{Pa}$) is indicated on the right hand axis. It can be seen that the playback sound was ramped up through the deep dive when the whale was clicking. The playback was ended in both cases within several minutes of cessation of vocalization.

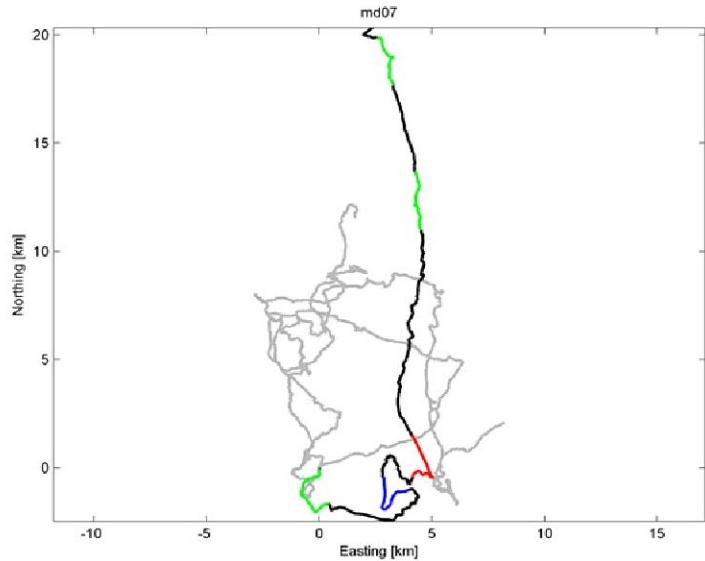


Figure 11. The patterns of movement, shown in a two-dimensional plan view, of four tagged Blainville's beaked whales when the whales made repeated deep foraging dives. These tracks are based upon assumptions about the speed of the whale and of currents, and the details of movements will be improved after points are georeferenced throughout the record. The track shown in multiple colors is of the female adult beaked whale involved in the playback, and this is superimposed on three indicated in grey for which there was no playback. Each track covers a similar time period. The black parts indicate parts of the track that were not deep foraging dives. The green sections show the pre- and post-playback dive; the blue section shows the track during the MFA sonar playback and the red section shows the track during the killer whale playback. Note that the pseudotracks on Figure 11 are not fully georeferenced as were the track segments illustrated in Figure 5, so they should be taken more as an integrated view of changes in heading than as a geographically precise track.

Analysis of heading data for response to playback

The heading data from the DTAG were analyzed in Matlab using non-parametric kernel density estimation. The data were split into two categories, pre-exposure headings and post-exposure headings, with the time at the end of the orca recording used as the breakpoint between the two. The change in angle between each heading was calculated and this was then used to calculate the kernel density estimate ($f(\theta)$) (Fisher 1995):

$$\hat{f}(\theta) = (nh)^{-1} \sum_{i=1}^n w\left(\frac{\theta - \theta_i}{h}\right) \quad (2)$$

Where:

$$w(\theta) = \begin{cases} 0.9375(1 - \theta^2)^2 & -1 \leq \theta \leq 1 \\ 0 & Otherwise \end{cases} \quad (3)$$

The kernel density estimate ($f(\theta)$) was then also calculated for 100 randomizations of the heading data order and the same breakpoint as that in the observed data was used. The log-likelihood ratio was then calculated for both the observed data and the randomized data and the p-value determined.

Figure 12 shows the rate of change in heading per second throughout the tag data for Md07_254a. It should be obvious that there are more changes in heading before the changepoint when the whale responded to playback, compared to the entire record after playback.

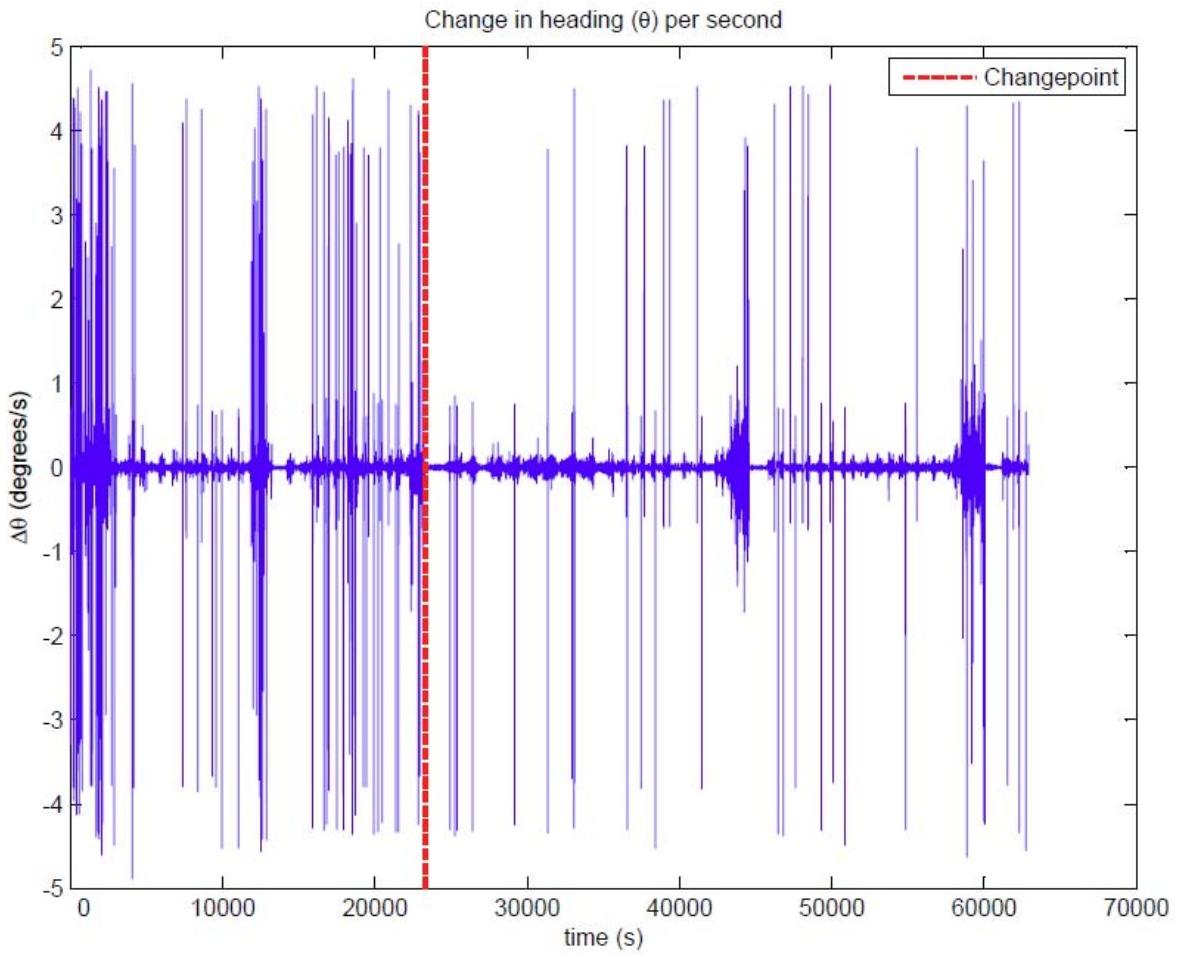


Figure 12. The change in heading data for the duration of the dive record. After the indicated changepoint the variance in the heading data is reduced as the whale heads on a relatively straight course.

Figure 13 shows the calculated likelihood ratio for the observed data as well as a histogram of the likelihood ratios calculated for the 100 randomization tests. The observed data point is obviously well outside the distribution of randomized values.

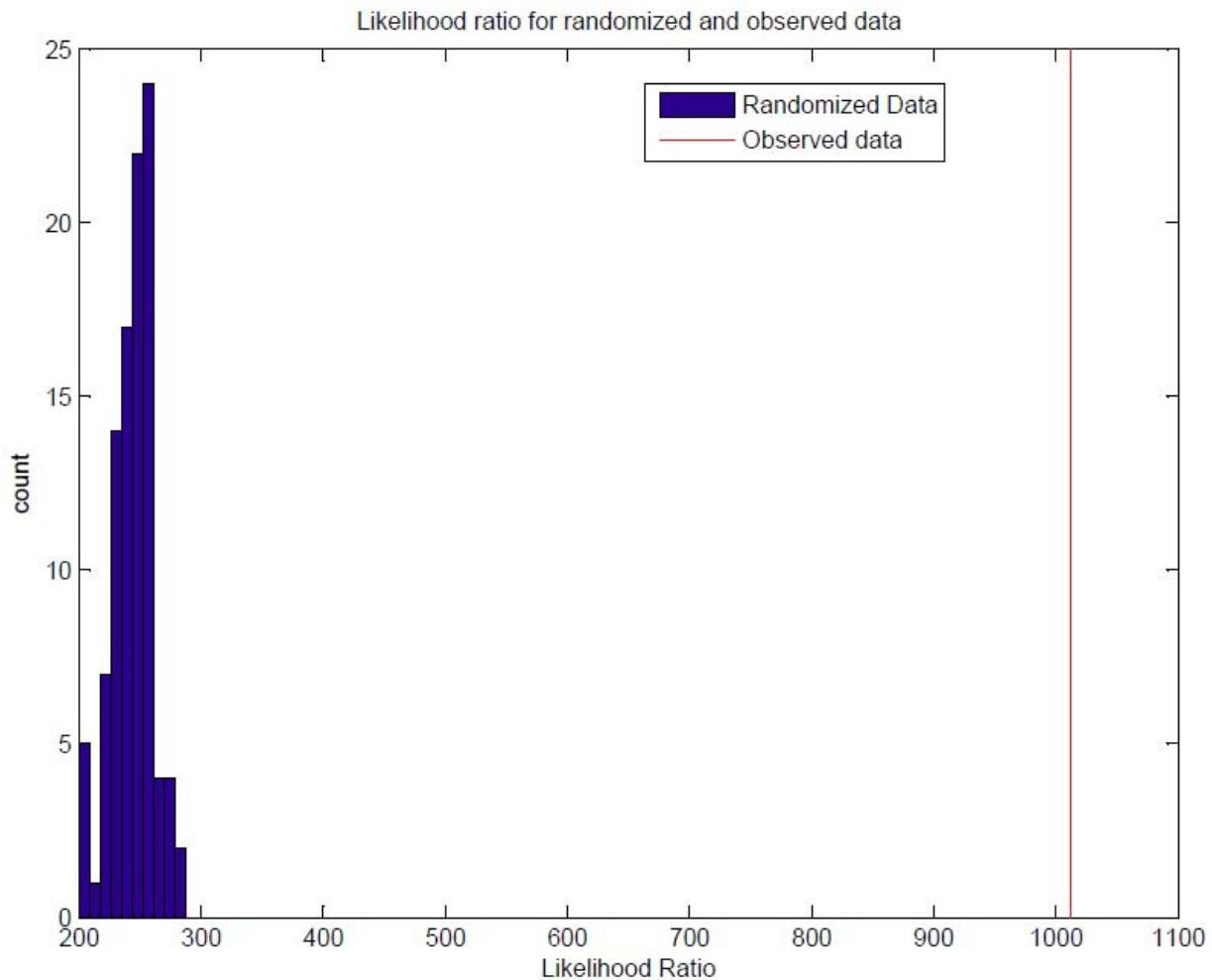


Figure 13. The calculated likelihood ratio for the observed data as well as a histogram of the likelihood ratios calculated for the 100 randomization tests.

Playback of PRN to Mesoplodon densirostris in 2007

The second beaked whale exposed to playback on the AUTEC range was a Blainville's beaked whale that was tagged on 27 September 2008 and exposed to a PRN stimulus with the same timing and overall bandwidth as the MFA playback from 2007. This whale stopped clicking early on the exposure dive, compared to the two pre-exposure dives or control dives from unexposed whales (Figure 14). The tag fell off during the ascent from this third dive, so data are not available on the duration or ascent rate of this dive. The exposure associated with this premature cessation of clicking was about 140 dB rms re 1 μ Pa.

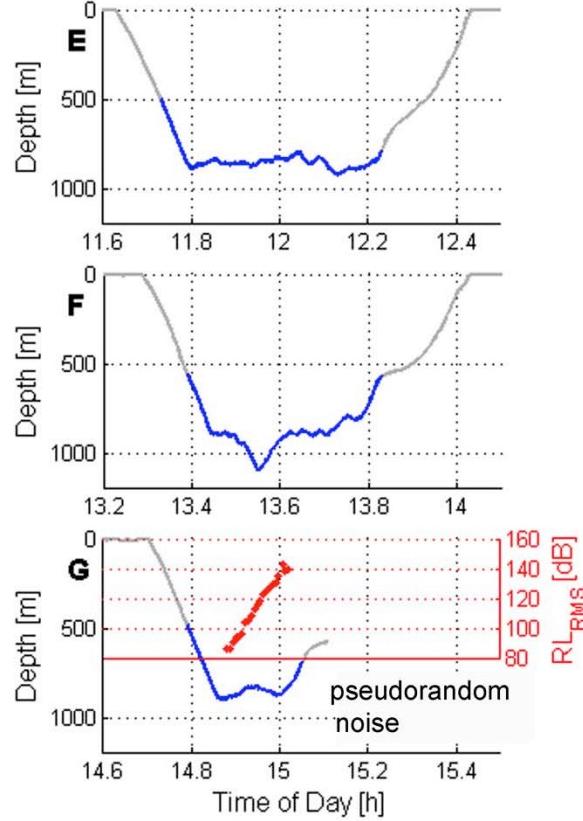


Figure 14. The first three dive profiles of the Blainville's beaked whale involved in the 2008 playback. The left hand axis shows the depth of the whale (gray:silent, blue:clicking) during the time that the tag was attached. During dive 3 the whale was exposed to a playback of PRN sounds. Each of the red diamonds shows when the tag on the whale received playback sound and the received sound level (dB_{rms} re $1 \mu Pa$) is indicated on the right hand axis. It can be seen that the playback sound was ramped up through the deep dive when the whale was clicking. The playback was ended within several minutes of cessation of vocalization. The duration of clicking during exposure was 14.7 min, considerably shorter than the duration of clicking during the first (29.5 min) and second (24.5 min) pre-exposure dives.

Response parameters analyzed in BRS playbacks

The response parameters used to analyze responses of Dtagged beaked whales to experimental playbacks were defined for each deep foraging dive of each Dtagged whale under baseline or exposure conditions. The responses include the following: pre-dive interval, descent rate, descent duration, duration of clicking, number of buzzes, buzz rate, duration of silent ascent, ascent rate, dive depth, dive duration, and post-dive interval. These parameters were defined following (Tyack et al. 2006a) based upon the audio and depth data from the tag. All of the tag acoustic data were audited by at least one person who scrolled through spectrograms and listened to the audio data where this was useful for interpreting the spectrogram. The descent phase of a deep foraging dive is considered to start the last time the whale leaves the surface before performing a deep dive in which it produces echolocation clicks, and to end when the whale starts echolocating. The descent duration is the time between these two events and the descent rate is

calculated from the depth at which the whale started clicking divided by the descent duration. The duration of clicking is the time from the first to last click of the dive. The ascent phase of the dive starts at the last regular click and ends when the whale next reaches the surface. The ascent duration is the time between these two events and the ascent rate is calculated from the depth at which the whale stopped clicking divided by the ascent duration. As Blainville's beaked whales echolocate to forage, they occasionally switch from regular search clicks to a buzz, which involves an increase of the repetition rate of clicking and use of a different kind of click (Johnson et al 2008). These buzzes are thought to represent attempts to capture prey (Johnson et al. 2004; Madsen et al. 2005). Along with the start and stop of regular echolocation clicks, the time for every buzz was noted in an audit of the tag audio data. The number of buzzes is defined as the total number of buzzes identified to the tagged whale during each dive, and the buzz rate is this number divided by the duration of clicking. The dive depth is the maximum depth recorded during each dive, and the dive duration is the time from when the whale left the surface to when it next surfaced at the end of the dive.

Dive depths and durations were available for 33 dives from 6 individuals. All other variables were measured in 25 dives from 6 individuals except for the intervals between deep dives where a sample size of 17 intervals was available and for the statistics of the ascent portion of the dive where there was a sample of 32 dives. The tag came off during the ascent portion of the dive when PRN was played back – this is the dive for which ascent data are missing. Variables were tested for normality using Shapiro-Wilk, Kolmogorov-Smirnov, Anderson-Darling and Cramér-von Mises tests. Duration of clicking, number of buzzes, descent duration were all found to be normally distributed. Dive depth and duration were transformed using a Box-Cox transformation with $\lambda=-2$. Descent rate, ascent rate and duration of silent ascent were log transformed. All transformed variables were normally distributed. Akaike's Information Criterion was used to determine the most parsimonious model in each case. The inclusion of all three independent fixed effects (playback, sex, and individual) was found to provide the best fit for most cases. In models of ascent rate and buzz rate, sex did not have a significant effect, but exclusion of sex as a fixed effect produced only slight improvement in the model fit. The models showed that there were significant differences in dive depth and duration, duration of clicking and post-dive interval between individual whales, but not in any other dive characteristic. Only two of the 6 individuals was a male but, in this case, sex appears to have had a significant effect upon duration of clicking, descent rate, descent duration and dive duration.

Table 4. Results of mixed effects models examining the effects of sound playback on dive variables in Blainville's beaked whales.

Dependent variable	Df	Playback		Individual		Sex	
		F	P	F	P	F	P
Duration of clicking	18	14.02	0.001 ***	3.65	0.024 *	4.95	0.039 *
No. Buzzes	18	10.81	0.004 ***	1.01	0.429	0.56	0.466
Buzz rate	18	0.05	0.820	0.66	0.629	0.58	0.455
Descent rate	18	0.79	0.386	1.54	0.233	9.79	0.006 ***
Descent duration	18	1.73	0.206	2.75	0.060	11.56	0.003 ***
Ascent rate	17	10.41	0.005 ***	1.94	0.150	2.13	0.162
Duration of silent ascent	17	11.50	0.004 ***	5.12	0.068	9.03	0.080
Dive duration	26	0.02	0.891	8.25	0.001 ***	16.49	0.004 ***
Dive depth	27	1.90	0.180	5.46	0.002 **	2.31	0.140
Pre-dive interval	11	0.92	0.358	0.49	0.699	2.90	0.117
Post-dive interval	11	5.88	0.034 *	4.70	0.024 *	4.10	0.067

A statistical analysis of response parameters of these beaked whales was performed comparing the 3 exposure dives to baseline dives. Most dive data were available for 33 dives from 6 individuals; all were baseline except for 3 dives of the 2 individuals exposed to acoustic playback. After accounting for the effects of differences between individuals and sex of the 2 playback and 4 baseline whales, foraging and ascent behaviors were significantly affected by the playbacks (Table 4). The playbacks resulted in a reduction in attempts to capture prey (judged by the number of buzzes), shorter foraging durations (judged by the production of clicks), reduced ascent rate, and increased ascent duration compared to the baseline foraging dives recorded from this species in the same location without playback. Dive variables that represented events in advance of playbacks (descent rate, duration and interval before the dive) did not differ between baseline and playback dives, but those occurring during or after playbacks (duration of clicking,

number of buzzes, ascent rate, duration of ascent and interval after the dive) were affected. Figure 15 plots the histograms of the values of exposure and baseline dives for all four of these parameters. The values for exposure dives, marked in red, are obvious outliers.

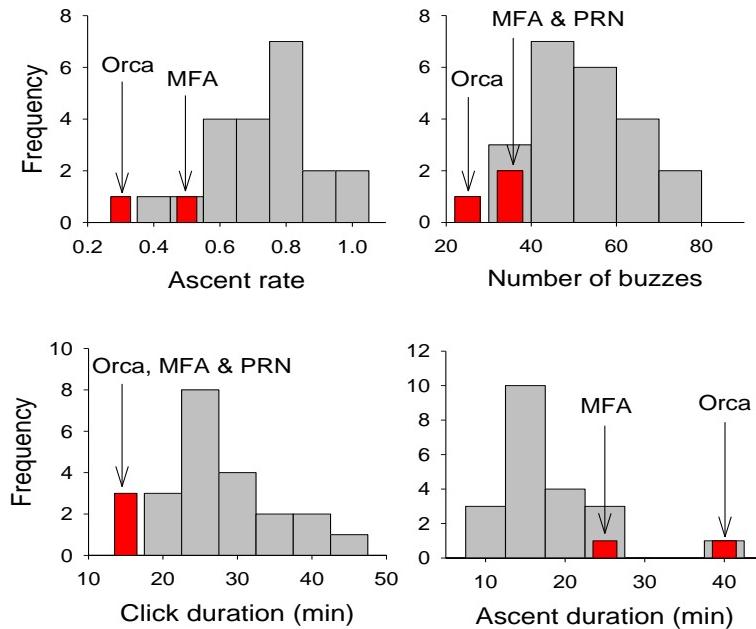


Figure 15. Histograms showing the frequency distributions of four variables measured across all the deep foraging dives for Blainville's beaked whales within the TOTO. The grey bars show those dives made without playbacks whereas the red bars represent the measurements made for the dives when playback occurred.

Summary of playback results

Taken together with the results of Aguilar et al. (2006), this small sample of preliminary results suggests that beaked whales silence and show avoidance responses to anthropogenic sounds in a surprisingly narrow 136–140 dB_{Brms} range (Table 5). A similar but more intense response was seen in response to the killer whale playback, which was elicited by an exposure at 98 dB_{Brms}, just barely above the ambient noise. After the killer whale playback, the beaked whale had a prolonged post-dive avoidance response. Nevertheless there remains an ambiguity in the interpretation of the killer whale playback; since the killer whale playback was the second in a series on the same animal, it is possible that the prolonged response was a consequence of the second exposure rather than the killer whale waveform. This suggests that carrying out additional killer whale playbacks should be a priority for future work to resolve this uncertainty. While these observations are drawn from just two individual beaked whales exposed to playback, this pattern of behavior has been measured against dives on control animals that were not exposed to a playback of any sound. The baseline tagged whales greatly strengthen the power of our statistical analyses.

Table 5. Summary of received sound pressure levels at which beaked whales respond to anthropogenic sounds.

<i>Ziphius cavirostris</i>	Ship propulsion	136~140 dB re 1 μ Pa rms broadband	Aguilar et al. (2006) Marine Mammal Science, 22(3): 690–699
<i>Mesoplodon densirostris</i> 2	PRN		BRS08
<i>Mesoplodon densirostris</i> 1	MFA		BRS07
<i>Mesoplodon densirostris</i> 1	Orca	~102 dB re 1 μ Pa rms broadband	BRS07

Playbacks of MFA, PRN and ORCA to non-beaked whales in 2007 and 2008

Data from playbacks to non-beaked whales in 2007 have been analyzed for vocal behavior recorded on the tag. In contrast to beaked whales, many delphinid species are highly social. They live in relatively large groups, making frequent use of sound to communicate in both affiliative and agonistic contexts, and may rely in some contexts on social defenses against predators or conspecific competitors rather than fleeing threats or employing acoustic crypsis (Tyack, 2000). It is possible that these species respond to acoustic stimuli by modifying their sound production or social behaviour, for example by changing group cohesion or whistle production patterns.

A change in whistle production patterns could involve whistling in response to the sound stimulus, perhaps even mimicking it. In contrast to most mammals, there is abundant evidence for delphinids imitating anthropogenic sounds (e.g. Richards et al. 1984). Some of the best evidence for such imitation involves relatively long-duration (seconds), tonal signals with acoustic features similar to those of MFA. Initial examination of the BRS DTAG sound recordings revealed several instances in which false killer whales (*Pseudorca crassidens*) produced whistles similar to the MFA signal just after its reception (see Figure 16 for an example). We therefore conducted a quantitative analysis to test whether false killer whales and the other delphinid species exposed to simulated MFA signals (pilot whales *Globicephala macrorhynchus* and melon-headed whales *Peponocephala electra*) responded to MFA by increasing whistle production rate and/or by mimicking the MFA sound.

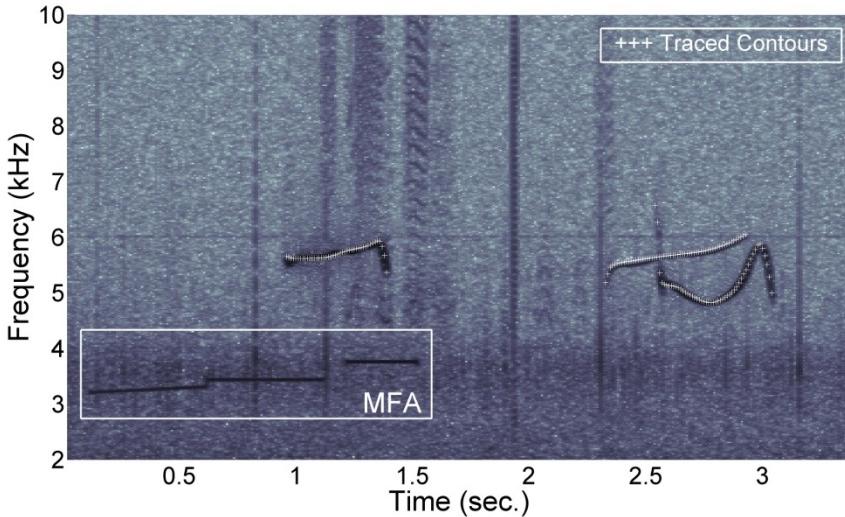


Figure 16. Spectrogram of DTAG acoustic data, showing the MFA signal (inside white box), as well as several false killer whale whistles and their traced contours (white crosses).

Whistle contours were traced using a semi-automated custom Matlab algorithm. Accuracy of all traced contours was verified by overlaying a plot of each traced contour on the spectrogram of the original whistle. An index of similarity between each whistle contour and the MFA signal contour was calculated using a dynamic time warping (DTW) metric (Buck and Tyack 1993); where a smaller DTW score indicates higher similarity, and the DTW score was set to infinity for any whistle whose duration differed more than 15-fold from MFA duration. Valid (finite) DTW scores were obtained for 617 of 701 whistles analyzed (88%). To test for a correlation between whistle and MFA similarity and the time since the last MFA reception, we fitted a straight line to the DTW score data and applied a rotation test (DeRuiter and Solow 2008), using the line's slope as the test statistic. Briefly, we tested the hypothesis that DTW score increases (i.e., whistles become less similar to the MFA signal) with increasing time since last MFA reception by comparing the observed slope of the DTW data with those obtained in 100,000 rotations of the dataset. We chose this test rather than a standard linear regression to account for autocorrelation in the time series of DTW scores caused by call-type matching.

We also applied a point-process time series model (Truccolo et al. 2005) to quantify whistle production rate and relate it to time since the last MFA reception, time since the first MFA reception, and number of whistles occurring in the preceding interval (the latter accounts for clustering and is analogous to the ensemble rates modeled by Truccolo et al. 2005). Intervals of 1, 5, 10, 20, 30, 40, 50, and 60 s were tested. If multiple intervals were significant at the $p < 0.01$ level (overall $p < 0.05$ with Bonferroni correction for multiple tests), one was selected based on Akaike's information criterion. A whistle start-time time series (with value 1 at whistle start times and 0 at all other times) was constructed for each group of whales using 0.01 s time steps, equal to the time resolution of our spectrograms. Models were fitted using generalized linear modeling (GLM) methods in R (<http://www.R-project.org>). We repeated the point-process analysis considering only imitative whistles - the subset of whistles most similar to the MFA. To select them, we plotted a histogram of DTW score, defining all whistles with a DTW score below 6.5×10^6 (the first peak in the bimodal histogram) as "imitative" (Figure 17).

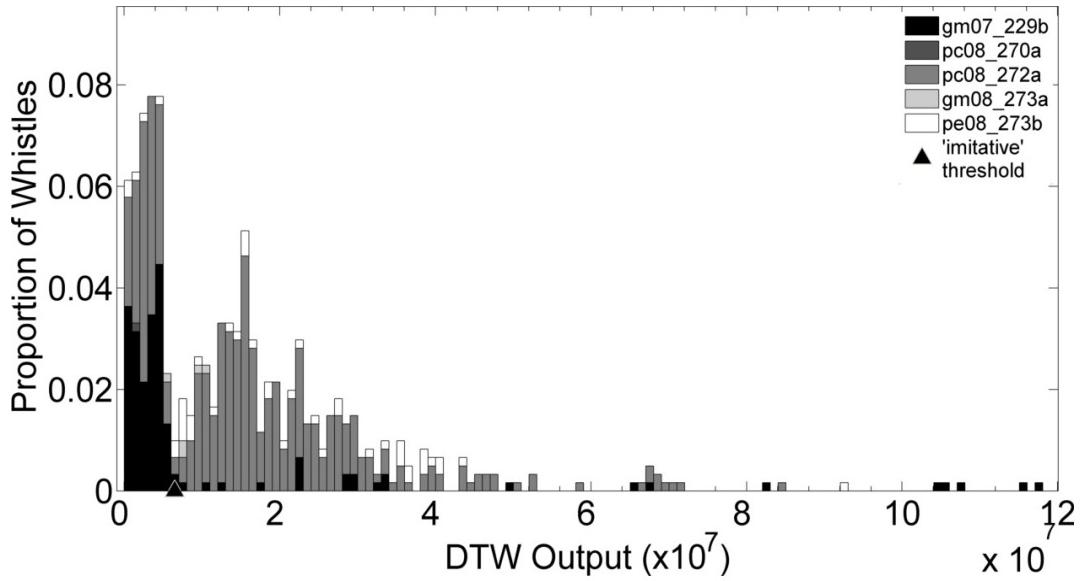


Figure 17. Distributions of DTW scores for whistles recorded on DTAG acoustic datasets from all five tagged animals. The threshold for whistles defined as imitative ($6.5e6$) is indicated by the black triangle on the x-axis.

Figure 18 shows all traced whistle contours. The number of whistles detected during the MFA exposure and contour-traced for further analysis varied from 4-466 per tag recording (Table 6).

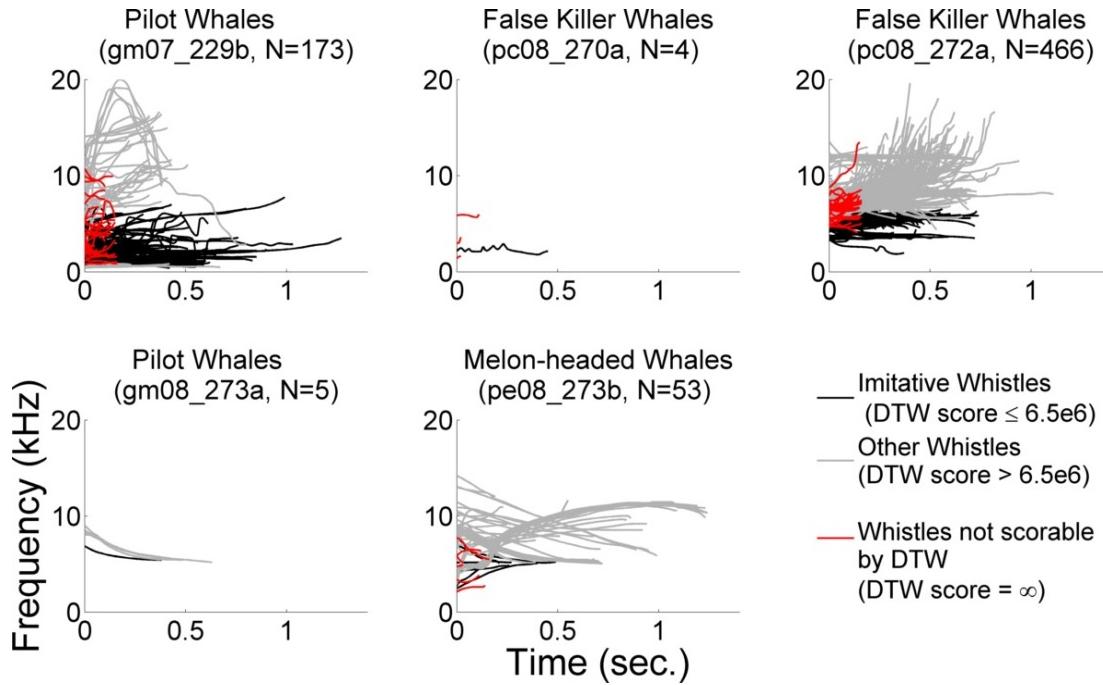


Figure 18. Traced contours of whistles detected on DTAG recordings from each of five tagged whales, presented as a function of time since start of whistle. Whistle contours are color-coded, with whistles classified as MFA-imitative in black and other whistles in grey. Whistles for which the DTW score was infinite (i.e., no valid DTW score could be calculated) are plotted as red lines.

One group of false killer whales (pc08_270a) and one group of pilot whales (gm08_273a) produced very few whistles during the MFA exposure (4-5 whistles total per group), and no clustering or autocorrelation of whistle times was detected for those groups, although the power of the tests was limited by the very small sample size. For all other groups, whistle times were clustered and auto-correlated. The point-process model took such clustering into account by allowing for dependence on whistle production rates in the preceding interval. This clustering parameter was significant ($p<0.05$) in all cases except when sample size was very small (under 10 whistles). The optimal interval size ranged from 5-30 seconds, indicating that the probability of whistle production was influenced by the number of whistles occurring in the preceding 5-30 sec. The dataset analyzed here was not large enough to detect any species-specific patterns in interval size. For the false killer whale group (pc08_272a), there was a weak positive relationship between DTW score and time since last MFA reception: whistle-MFA similarity was highest immediately following each MFA reception (Table 6). Other groups showed no trends (Table 6).

Table 6. Results of statistical analysis of whistle time series.

Basic Data		Measures of Clustering		Correlation/ Rotation Test*	Point Process Model Parameters (All Whistles)**				Point Process Model Parameters (Imitative Whistles Only)**			
Trial ID	N Whistles (N Imitative)	Greenwood's Statistic (p)	Autocorrelation (p)	Intercept, Slope (p)	Intercept (p)	Time Since Last MFA (p)	Time in Exposure (p)	Preceding Interval (p, N sec.)** *	Intercept (p)	Time Since MFA (p)	Time in Exposure (p)	Preceding Interval (p, N sec.)
Gm07_29b	173 (114)	<1e-5	0.0045	2.1e7, - 4.0e5 (0.85)	-6.9 (<2e- 16)	0.015 (0.14)	-3.0e-4 (0.22)	0.22 (<2e- 16, 10)	-7.3 (<2e- 16)	0.02 (0.07)	-2.9e-4 (0.35)	0.28 (2.2e- 12, 10)
Gm08_273a	5 (1)	0.15	0.72	6.1e6, 1.2e5 (0.20)	-8.3 (<2e- 16)	0.085 (0.22)	- (0.79)	n/a (>0.4, all)	-2.8e4 (0.60)	42 (0.61)	540 (0.60)	n/a (>0.9, all)
Pc08_270a	4 (1)	0.066	0.013	0, 7.3e4 (0.75)	-10.0 (<2e- 16)	0.028 (0.68)	- (0.56)	1.8 (0.033, 5)	-2.0e4 (0.63)	400 (0.63)	210 (0.63)	n/a (>0.9, all)
Pc08_272a	466 (116)	<1e-5	<1e-5	1.5e7, 1.7e5 (0.029)	-5.5 (<2e- 16)	-0.042 (2.4e- 10)	-1.3e-5 (0.96)	0.041 (<2e- 16, 30)	-5.4 (<2e- 16)	0.09 (7.7e- 8)	- (0.005 5)	0.064 (0.001 3, 30)
Pe08_273b	53 (7)	1e-5	<1e-5	2.6e7, - 3.0e5 (0.81)	-8.4 (<2e- 16)	0.053 (0.006 8)	-5.5e-4 (0.35)	0.25 (1.4e- 4, 20)	-9.2 (<2e- 16)	0.06 (0.23)	8.5e-4 (0.65)	n/a (>0.2, all)

Gray shading indicates results that were not statistically significant at the $p < 0.05$ level.

Non-significant parameters were not included in the final point process models.

*Correlation/Rotation Test tested the null hypothesis of no correlation between dynamic time warping score (whistle-MFA similarity) and time since last MFA reception.

**Point Process Models fit a model for whistle production rate, potentially including effects of time since last MFA reception, overall time since start of exposure, and whistle rate in the preceding seconds. (See Methods section for further detail.)

***The effective significance level for this test was $p < 0.01$ rather than 0.05 (Bonferroni correction for multiple comparisons).

Point process analysis results for the false killer whale (pc08_272a) group confirmed the rotation test findings, as both overall and imitative whistle rates were inversely related to time since last MFA reception (Table 6). There was also a slight reduction in imitative whistle rate, but not overall whistle rate, as overall time since start of exposure (and MFA received levels) increased. The only other trend observed in the data was an increase in overall whistle rate by the melon-headed whales as a function of time since last MFA reception (that is, a transient reduction in whistle rate immediately following each MFA reception) (Table 6).

The results of these analyses support the hypothesis that one false killer whale group responded to MFA by mimicking the MFA signal: the group whistled more immediately following each MFA reception, and whistle-MFA similarity decreased with time since the last reception. This result confirms previous anecdotal reports that delphinids “whistle back” at and imitate sonars and other active acoustic devices. Our findings are also consistent with Rendell and Gordon’s (1999) opportunistic observations of a group of long-finned pilot whales (*Globicephala melas*),

which increased whistle rates immediately following periodic receptions of 4-5 kHz military sonar transmissions, though they did not increase production rates of the whistle type most similar to the sonar signal. We did not observe mimicry or vocal response to the MFA signal by any of the other four delphinid groups we studied; in fact, the melon-headed whales had lower whistle rates immediately after individual MFA receptions.

Other data used for preliminary description of possible responses in the 2007 and 2008 playbacks come from dive records on the tag and observations made by visual observers on the vessels near the whales. All of these other species are often referred to as members of a group of odontocetes informally referred to as blackfish, a term we will use here for the non-beaked whale group of odontocete subjects for CEEs. Although reactions to sonar sounds and control sounds were observed in blackfish in some cases, there was little consistency in the responses observed. The beaked whales showed premature silencing and surfacing in response to all playbacks, along with prolonged avoidance to the killer whale playback. The blackfish tested showed much more variable responses in dive behavior and vocal and avoidance behavior. While some blackfish did swim away from the sound source during playback, there was no prolonged avoidance behavior of the sort observed with the beaked whale exposed to killer whale calls. For example, figure 19 illustrates the track of a tagged pilot whale that showed no avoidance behavior during playback to MFA sonar and then playback of killer whale sounds. During some playbacks to blackfish, the visual observers described the whales as increasing their rate of travel during the playback, but during other playbacks such as the one illustrated above, the whales slowed down and increased group cohesion. While these responses of blackfish to playback were varied, they all were clearly different from the responses of beaked whales to playback of the same sound stimuli.

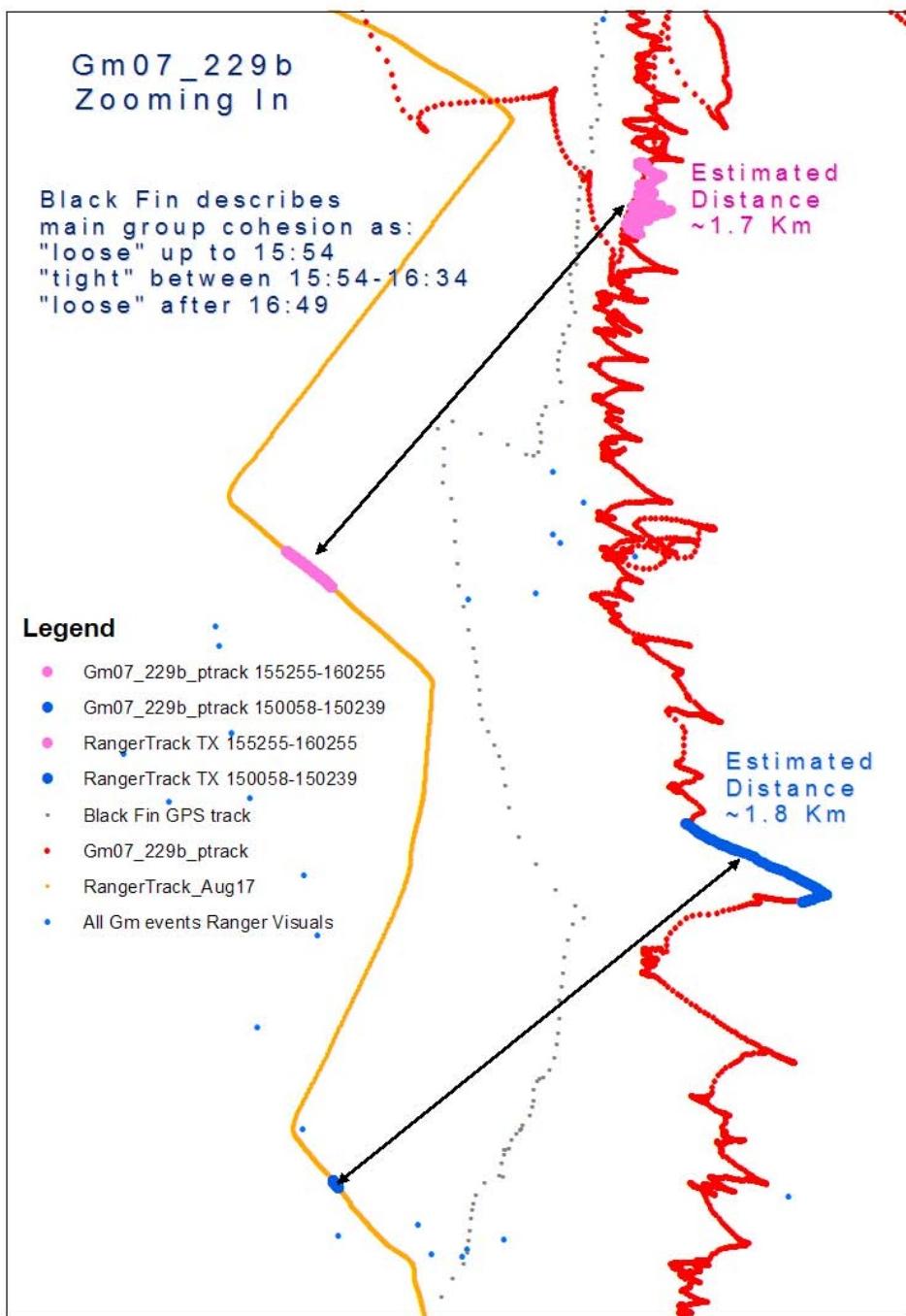


Figure 19. Plot of location of Source Ship MV Ranger, and track of the pilot whale Gm07_229b that was exposed to a playback of MFA Sonar (blue parts of the tracks), followed by a playback of killer whale (pink parts of the tracks).

Interpretation of playback results

These data are consistent with the conclusion that, similar to harbor porpoises (Southall et al. 2007), beaked whales are particularly sensitive in terms of behavioral responses to acoustic exposure. In the U.S., regulators have a separate exposure criterion for harbor porpoise compared

to other cetaceans. Regulators predict that any exposure above 120 dB SPL will disturb behavior in porpoises, while a variety of higher criteria are used for other species (Southall et al. 2007). Our results support a similar criterion of about 140 dB SPL for beaked whale exposure to mid-frequency sounds. Our results do support a lower acoustic threshold of disturbance for beaked whales than is currently applied in the U.S. However, more data from beaked whales are required to finalize a dose:response function, and analyses of similar experiments with different species are required to support the interpretation that other species may be less sensitive than beaked whales. The research described here has pioneered the techniques that will be required to complete the understanding of how beaked and other whales respond to sonar and other sounds, and to define the function relating acoustic dosage and behavioral response.

Results & Discussion for Development of DTAG-3

This section provides details on the design and construction of the new DTAG-3. Combining a set of miniaturization strategies has led to a tag design with the dimensions shown in Figure 20. The tag has 2.5-6 times the recording duration of DTAG-2 and incorporates both a GPS and gyroscopic sensor. Compared with DTAG-2, the new tag has about one half of the overall volume and footprint on the animal making it practical to apply to smaller delphinids. The smaller, lighter tag will also be easier to deploy resulting in more secure and more accurately placed attachments. This is likely to extend the duration of attachments in most species. Accuracy in the placement of the tag on the whale is of special importance to ensure correct antenna placement for regular GPS positioning.

Although the processor used in the new tag consumes less power per operation than that used in DTAG-2, improved code efficiency is also needed to achieve the power consumption target. The computational bottleneck in the DTAG-2 is the loss-less audio compression algorithm used to compress the hydrophone data. This algorithm, called X3 and developed under a previous SERDP grant, is a critical component in DTAG-2, effectively tripling the tag recording duration as compared to a non-compressing tag. The X3 implementation in DTAG-2 is written in assembly language and so is as efficient as possible for the processor in that tag. Through careful profiling, a highly efficient version of X3 has been written for the processor on DTAG-3. This new implementation requires 70% fewer computations than the DTAG-2 implementation and is a key enabler for long recording duration in the new tag.

With the smaller package size of DTAG-3, the antenna length must be reduced accordingly to maintain mechanical stability. The antenna is used by the VHF beacon and is a critical determinant of detection range. On DTAG-2, a 1/4 wavelength whip antenna was used measuring about 18" for beacon frequencies in the 148 MHz range. Nickel-titanium rod was used due to the high strength-to-weight ratio and excellent flexibility of this alloy. The length of the antenna necessitated care in the design of the tag (specifically the center-of-buoyancy / center-of-mass separation) to ensure that the antenna was held vertically out of the water in most sea-states. In the new tag design, a reduction in length from 18" to 10" has been achieved by increasing the transmit frequency to 220 MHz, the highest frequency band covered by commercial animal telemetry receivers, and by choosing a coil-loaded 1/5 wavelength design. The theoretical loss of performance of this design over the DTAG-2 radiator is modest (<2 dB) and can be recouped by increasing the transmit power.

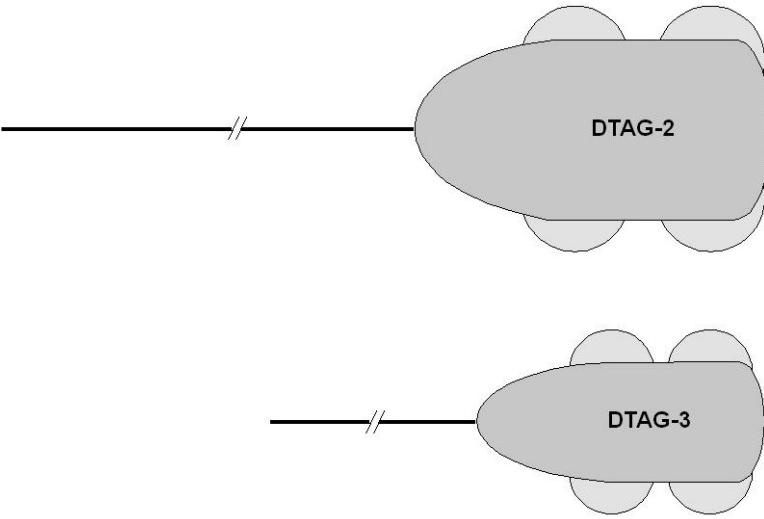


Figure 20. Comparative size of the current DTAG-2 and the new DTAG-3. Antennas are shown with a scale of 50% to fit in the page. Dimensions of DTAG-2 when attached to a whale are 8.5"x3.9"x1.6". Dimensions for DTAG-3 are 6"x2.5x1.2". Antenna lengths are 18" and 10" for DTAG-2 and DTAG-3, respectively. The footprints of the suction cups on the whale are 29 sq-in and 17 sq-in, for the old and new designs, respectively.

Integrated design to reduce volume, lower power and increase capability

Longer Attachments

The key to increasing attachment times is miniaturizing the tag. Achieving longer attachment times without losing functionality requires more memory and longer battery life, both of which dictate a larger tag. Our approach was to tightly integrate the mechanical, electrical, and software designs to maximize space utilization and power efficiency. Ultra-low power circuits were developed for sensors and sound sampling while custom signal processing and compression software was developed to maximize data recorded per Joule. A volume reduction goal of 50% from DTAG-2 to DTAG-3 presented many challenges, therefore it was clear that in order to reduce the overall volume we needed a detailed analysis of all circuit components, sensors, housing and attachment components. By integrating the design we were able to determine what effect each component change would have on others. Our methodology followed the following logic: smaller sensors and circuit components lead to smaller and lighter printed circuit boards (PCBs); smaller PCBs lead to smaller and lighter electronic housings; overall reduced weight leads to reduced flotation requirements which reduces the size of the syntactic foam and ultimately a smaller overall package.

Printed Circuit Boards, Battery

The PCBs, pressure sensor, accelerometers, flash memory chips and lithium battery are among the heaviest components in the tag and thus have a large impact on the volume. Carefully

scrutinizing each circuit in the new tag along with lowering the power consumption lead to a 40% reduction in the weight required for PCBs, sensors and battery. (see figure 21)

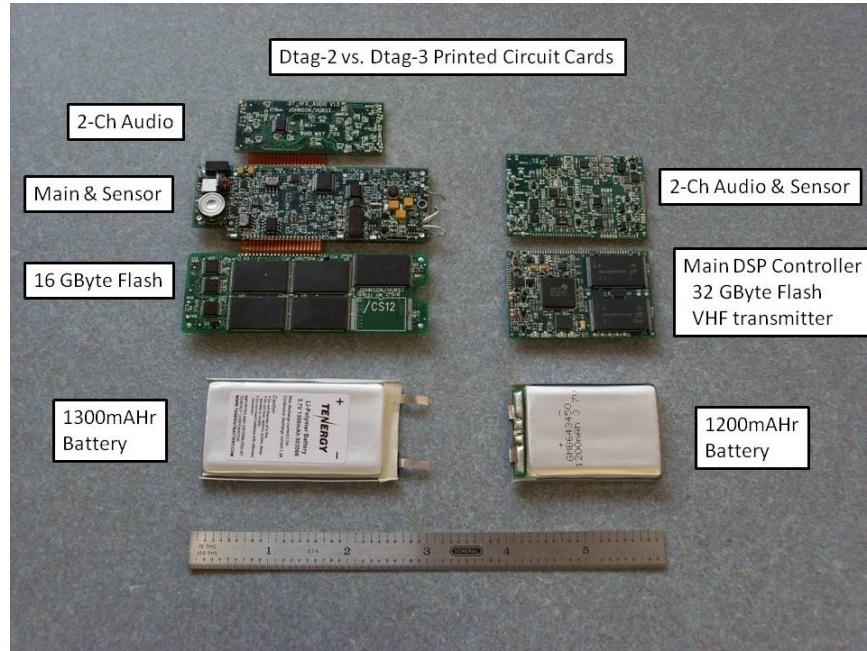


Figure 21. Printed circuit boards and battery; DTAG-2 (left hand side) vs. DTAG-3 (right hand side) shown against a 6" ruler.

To accomplish this task while adding capability we started by balancing the size of available lithium polymer batteries with the PCB area the new tag circuitry required. The result was an area of 17 cm^2 as opposed to a DTAG-2 area of 25 cm^2 . We also went exclusively with 0.08 cm thick circuit boards; the resulting volume dropped from 7 cm^3 to 2.7 cm^3 and the weight from 28 grams to 11 grams. The thinner circuit boards are not as strong as standard 0.16 cm material. These PCBs are expected to see pressures of up to 200 bar as animals dive to 2000m. Flexing under hydrostatic pressure at these great depths, due to compression of materials, was a major concern. We needed to come up with a means of mounting them that would isolate this compression. Our decision was to mold flexible urethane shoulders into the electronics housing to minimize the compression force on the boards while still holding them securely in place (see figure 22).

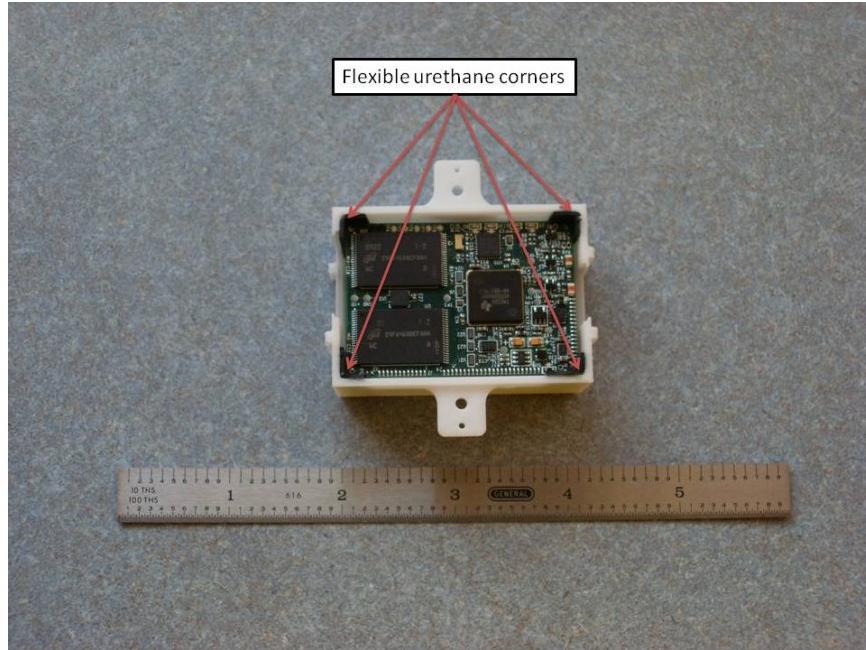


Figure 22. DTAG flexible urethane shoulders in the electronics housing.

Longer attachments required that the battery capacity not be reduced. Lowering the overall power consumption of the new tag while maintaining the battery capacity results in longer tag-on times. No tangible weight reduction was expected for the batteries as the energy densities of lithium polymers are fairly constant (we did go from a 10 cm³ cell to an 8.7 cm³ cell; both of which are 22 grams). However, the form factor was changed to facilitate the desired instrument shape.

Flash Memory

The number of flash memory chips was reduced from as many as 12 in DTAG-2 to 4 for the new tag; a savings of 4 grams. However due to the availability of denser flash the overall memory was increased from 16 GBytes to 32 GBytes. This is also an important consideration in longer attachment times. The pressure, accelerometer and compass sensors were also dramatically reduced in size and weight (see figure 23).

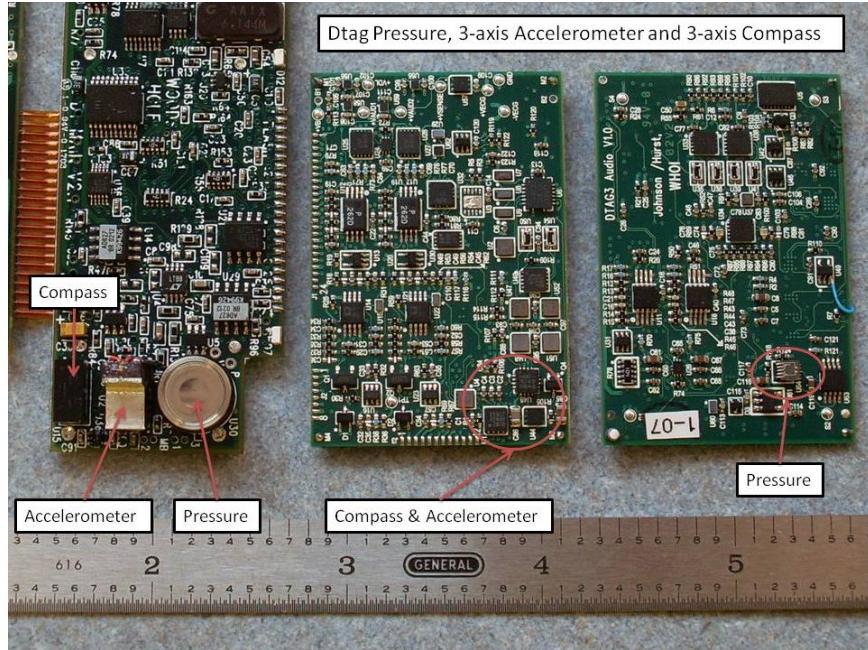


Figure 23. Photograph of sensors on DTAG-2 (left) and DTAG-3 (center and right)

Very High Frequency Radio Beacon

As with all archival tags, the DTAGs contain a VHF beacon to enable tracking and recovery of the tags. The VHF radio tracking system for the DTAG-2 consisted of an OEM (original equipment manufacturers) transmitter circuit at 148–152 MHz, 2 OEM CR-1/3N lithium batteries to power the transmitter and a 46 cm antenna made from 0.09 cm diameter nickel-titanium wire. The transmitter was purchased ready-made and molded into the syntactic foam tail together with batteries independent of the main tag electronics. To meet the challenging size target of the DTAG-3, we had to dispense with an independent VHF battery, reduce the antenna size, and integrate the VHF beacon into the main electronic compartment. Working with ATS Telemetry, the OEM transmitter manufacturer, we included the transmitter circuitry on the new Main PCB. This allows it to be powered by the tag battery, eliminating the need for separate batteries thus saving 15g of weight. It also allows the transmitter to be under program control. Turning it off completely when under water and managing its pulse rate while at the surface are two ways that save considerable power in this system.

The design goal of reducing the antenna size dictated a change upwards in beacon frequency, which had ramifications on the circuit design. After lengthy evaluation, we decided on a beacon frequency of 220 MHz, a 50% increase on the DTAG-2 frequency of 148 MHz. The benefits of this frequency are (i) shorter antenna length for a given radiation efficiency, and (ii) compatibility with commercially available telemetry receivers. To generate the 220 MHz carrier from commercially available crystals in pressure tolerant housings (unlike most electronic components, crystals require an air-space around the quartz element and so require a strong housing to survive high pressure), we designed a two transistor oscillator and frequency quadrupler circuit with the output matched to the fifth-wavelength antenna. Such a short antenna requires a ground plane counterpoise to be an effective radiator. Initially, we expected that the salt water surrounding the tag would act as a ground plane but after extensive testing with a high

frequency spectrum analyzer, we discovered that salt-water was in fact a poor ground plane. Covering most of the tag body with copper foil (about 50 cm²) before over-potting with urethane created an improved ground plane.

A set of field tests were performed to verify satisfactory operation of the beacon, which is perhaps the most critical sub-system in the tag, as it must function correctly for the tag and data to be successfully recovered. Comparative tests were performed in two different locations with 10-15 km sightlines between transmitter and receiver. In both cases, DTAG-2 (148 MHz) and DTAG-3 (220 MHz) beacons were placed side-by-side at the transmitter location, and the received level compared with a variety of antennas. Once the ground-plane was installed, the DTAG-3 transmitter gave substantially higher received levels than the DTAG-2 transmitter. On several occasions, DTAG-2s have been located by radio at distances of 40 or more nautical miles with suitably elevated receiving locations to overcome earth's curvature. Our objective in designing the DTAG-3 transmitter was to obtain comparable performance to the DTAG-2 and test results indicate that this has been more than fulfilled.

Audio sampling

Devices for on-animal sound recording need a wide dynamic range to capture both the calls made by the tagged animal and weak sounds including ambient noise in the environment or echoes from organisms (Johnson et al. 2009). But producing a low-power device with wide dynamic range is challenging, requiring special circuit techniques throughout the audio chain comprising preamplifier, anti-alias filter and ADC. The usual approach, and the one adopted in previous DTAGs, is to use a sigma-delta ADC, a type of over-sampling convertor that relaxes the requirements for anti-alias filtering. By minimizing the anti-alias filter, a source of electrical noise and power consumption is reduced. Sigma-delta ADCs are ubiquitous in portable audio appliances such as MP3 players and telephones. However, these convertors are optimized for the human audible frequency range and few are capable of sampling at the rates needed for high frequency delphinids. The few fast sampling sigma-delta ADCs currently available have unacceptably high power consumption. The approach taken in the DTAG-3 design was to use a conventional low-power 16-bit ADC (a successive approximation convertor) but to sample at a rate 2-5 times higher than necessary. This relaxes the anti-alias filter requirement, facilitating the goals of low-power and wide dynamic range but at the expense of a much higher data rate to be stored in memory. To overcome this problem, digital decimation is implemented in the tag DSP to reduce the sampling-rate. The result is a low-power, wide band acquisition system that approaches the performance of a much higher power sigma-delta convertor. The practical upper limit for wide-band dynamic range in a small battery-powered appliance is about 93dB, and the DTAG-3 performance is close to this value. Given this dynamic range, only two user-selectable gain options are necessary, simplifying configuration of the tag. The lowest gain option is chosen so that electrical noise from the ADC dominates the noise floor of the tag. This gain mode realizes the maximum dynamic range of the convertor and results in a clipping level (i.e., the sound level above which the recording will be distorted) about equal to the maximum sound level that would be received from the tagged animal (about 180 dB re 1 µPa peak at the usual tag location posterior of the sound source). The highest gain option is chosen so that preamplifier noise rather than ADC noise sets the tag noise floor. In this mode the tag is maximally sensitive to low-level sounds but will clip at lower received levels. The two gain settings can then be

considered 'maximum dynamic range' and 'maximum sensitivity', making it straightforward to select a gain for a given tagging study.

Audio

The new tag contains 2 independent, synchronously sampled audio channels, one of which is shown in the figure 24. Each audio channel comprises: a piezo-electric ceramic element; a low power, low noise input preamplifier; a programmable (hi/low) gain stage; an anti-alias filter and differential analog-to-digital converter (ADC) drive stage and a 16-bit ADC. Audio data are sampled, stored in flash memory and offloaded as wav files. The resulting data stream has an effective gain of -173 dB re 1V/ μ Pa with a clipping level of 1V, so the maximum input to the new tag before clipping is 173 dB re μ Pa.

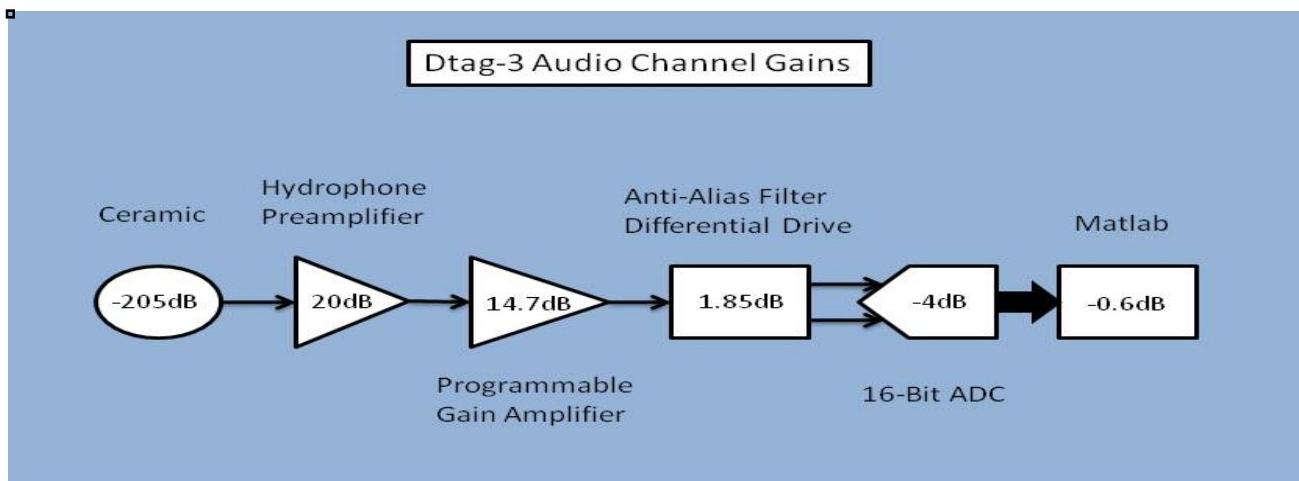


Figure 24. Flow diagram of audio data in DTAG-3.

Hydrophone

The hydrophone is the same as that used for DTAG-2. This is a spherical element with a 9.5 mm (0.375") diameter made from 5400 LZT (lead zirconate titanate) (Navy I) piezo-ceramic with 1 mm wall thickness. This hydrophone has the following nominal properties:

Resonance frequency of:	203 kHz	$f_r = N_{sp}/d_m$
Sensitivity of:	-205 dB re V/ μ Pa	$V/P = g_{31}d_oP/2$
Capacitance of:	2.6 nF	$C = \pi K_3 \epsilon_0 d_m^2/t$

where:

N_{sp} is the frequency constant for a sphere (1730 Hz/m)

g_{31} is the 3-1 mode piezoelectric constant (-11.7×10^{-3} Vm/N)

K_3 is the relative dielectric constant (1300 no units)

ϵ_0 is the permittivity of free space (8.85×10^{-12} F/m)

d_o is the outer diameter (m)

d_m is the mean diameter (m)

t is the wall thickness (m)

P is the applied pressure (Pa)

Hydrophone Preamplifier

The preamp has a discrete FET front-end to reduce noise and a fixed gain of 20 dB. The preamp noise voltage is calculated to be about $1.5 \text{ nV}/\sqrt{\text{Hz}}$ at high frequencies giving a referred-to-input (RTI) noise floor of 29 dB re $\mu\text{Pa}/\sqrt{\text{Hz}}$ with this ceramic.

Digital Signal Processor and microcontroller

In keeping with previous DTAGs, the DTAG-3 design is centered around a DSP. Compared to conventional microprocessors, DSPs have dedicated computational units for common operations used in filtering, decimating, and compressing of time-series data. Data compression in particular is important for sound recording tags to extend the memory capacity. Using a DSP enables flexibility in the balance between on-board processing and memory storage rate. The DSP chosen, a Texas Instruments TMS320C5509A is a compact low-power device with a USB interface, further reducing the circuit complexity. A disadvantage of most DSPs is that they tend to lack an ultra-low power monitoring mode. Such a mode is required in a tag to detect start-up conditions (e.g., immersion in salt-water) and to control essential services like the VHF beacon. To implement these capabilities, an ultra-low power microcontroller (a Texas Instruments MSP430F2112) was added to the design. This device has a miniature package and is programmed directly by the DSP avoiding complex software installation procedures in the tag.

Global Positioning System

Commercially-available GPS receivers are unsuitable for use on diving marine animals because the time required to determine a position is frequently longer than the surfacing time of the animal. Two factors dominate the acquisition time: (i) a computationally-demanding search over code- and Doppler-space must be performed by the receiver to find satellite signals, and (ii) the navigation code transmitted by each satellite must be monitored for up to 6 seconds to determine the time of transmission, a critical variable in the ranging equations (Grewel et al. 2001). To overcome these limitations in the DTAG-3, the GPS positioning calculations are performed off-line (i.e., after recovery of the tag) using web-published almanacs of satellite positions. Using this technique, only short (100 ms) samples of the GPS baseband signal are required to extract a position, provided that the local clock on the tag does not drift more than 20 ms (a fundamental GPS timing interval) between surfacings. To minimize processing on the tag, the baseband signal is sampled and stored directly in memory requiring approximately 100 kbytes of memory per position. This memory utilization amounts to 1 Gbyte/week at 1 position/minute and so is small in comparison to the audio data rate. Once the tag is recovered, the recorded signals are batch-processed using a software GPS receiver implemented in Matlab. The required low-drift clock is obtained on the tag by measuring the temperature of the timing crystal and integrating compensation values from a look up table.

Although the GPS methodology was tested at bench-level during the tag design phase with good results, two practical issues emerged during design and prototype testing. The first was the difficulty in purchasing GPS receiver components. Most components for GPS receivers are produced by specialized companies rather than the usual industry-leading semiconductor houses, and the chips are generally sold directly to OEMs. There is little market for small quantities of GPS chips and we eventually had to rely on offshore brokers to obtain components. This problem will likely persist in the future, making continued supply of the same components difficult to ensure. The second issue relates to electrical interference coupling from the tag circuit

into the GPS antenna. The original plan was to locate the antenna on the GPS circuit board but this was found to give poor performance in prototype testing. A revised circuit in which the antenna is mounted outside of the electronic package and wired to the GPS board is currently being assembled and evaluated.

Gyroscope

Absence of a speed sensor in previous versions of the DTAG has restricted our ability to track tagged animals through dives. Although the surfacing position of a tagged animal can often be estimated fairly accurately from visual observations (or in the new tag, from GPS fixes), unless acoustic receivers or transponders are deployed around animals, the only option for tracking animals below the surface is dead-reckoning (Wilson and Wilson, 1988). A dead-reckoned track is formed by integrating the estimated 3-dimensional velocity vector of the animal with respect to time. Although velocity is the integral of acceleration, accelerometers cannot be used by themselves to estimate velocity because these sensors measure both the animal's specific acceleration (the quantity required) and its orientation with respect to the gravity vector. The usual solution to this problem in underwater vehicles, where power consumption is not an issue, is to derive orientation independently of the accelerometers from a set of three gyroscopes. The known orientation is then used to isolate the specific acceleration signal from the accelerometers, which can be integrated to get the platform velocity vector (Grewel et al. 2001). This sensor suite, comprising triaxial accelerometers and triaxial gyroscopes, is known as an inertial measurement unit (IMU). Gyroscopes measure the angular rate about an axis, for example, yaw rate is the rate of turn about the dorso-ventral axis. Integration of the yaw rate gives the yaw which can be combined with a reference heading (e.g., from periodic compass measurements) to estimate the heading as a function of time. Similar computations, using periodic accelerometer corrections, give the pitch and roll. Until recently, gyroscopes have not been available in a sufficiently small form factor or with sufficiently low power consumption to be suitable for use in tags. A number of other sensors and data processing methods have been developed to estimate speed and so avoid reliance on gyroscopes in animal tags (Zimmer et al. 2003, Wilson et al. 2007, Johnson et al. 2009). However, because speed errors are integrated in forming the dead-reckoned track, positional errors grow with time and can easily reach hundreds of meters during a long foraging dive. Recently, micro-machined (MEMS) gyroscopes have become available in small ($<50\text{mm}^3$) packages and with relatively low power consumption ($<5\text{mA}$ per axis) making this important sensor modality now practical for tags. There are, however, several considerations in using gyroscopes. MEMS gyroscopes function by measuring the inertial forces on an oscillating frame. Oscillatory movement is an essential feature of any gyroscope but, when integrated into a tag, this movement is a sound source which can interfere with on-animal sound recording and may even be audible to the host animal (Hurst and Johnson, 2009). MEMS gyroscopes oscillate at 25–30kHz, and so coincide with the most sensitive hearing range of many delphinids (Richardson et al. 1995) and, judging from their vocalizations and initial audiograms, beaked whales (Cook et al. 2006, Finneran et al. 2008, Johnson et al., 2006). To reduce coupling of sound into the water from the gyroscope, we placed the gyroscope inside a cavity in the syntactic foam tail of the tag. A second issue with low-cost, low-power gyroscopes is that the zero-rate bias can vary substantially over time meaning that the orientation of a static animal will appear to change slowly. This error is usually corrected by a combination of Kalman filtering and periodic sensor resetting (Grewel et al. 2001) and we have implemented both approaches in post-processing. However recent field testing indicates that the zero-rate bias may be especially

sensitive to pressure in some, but not all, gyroscope axes, and that the resulting bias variability may be difficult to correct in animals that dive rapidly. The pressure sensitivity appears to relate to the packaging of the gyroscopes and we are continuing to examine methods to stiffen the packages to overcome this problem.

Electrocardiogram

The skin surface electrical potential of animals is a powerful and widely-used indicator of muscle activity whether due to heart contractions, breathing or locomotion. The traditional application is in heart-rate sensing in which appropriately-placed electrodes are processed differentially to accentuate the surface electrical signal from the heart muscles and attenuate electrical signals from other sources. Heart-rate is a valuable physiological indicator for studies of energetics, diving response, and startle (e.g., due to unexpected or alarming sounds in the environment, Götz 2008). With well-placed electrodes spanning the torso around the heart, cardiographic surface electrical potentials of a few millivolts are obtained, making this a trivial signal to detect above background electrical noise. The key is to space the electrodes maximally around the torso. However, in a small dorsally-located tag, especially one which will be attached with minimal animal handling time, there is no opportunity to space electrodes widely. If the electrodes are to remain within the footprint of the tag, the design described here allows only a 5 cm spacing which represents a very small angle when subtended back to the heart even in a small delphinid. For a dolphin or beaked whale with a body radius of 0.5 m at the torso, a 5 cm electrode spacing will result in a cardiac surface potential of 10-100s of microvolts, making this signal much more difficult to detect against electrical noise from other muscle activity. To alleviate this problem, we included two differential ECG channels in the tag, allowing a small array of surface sensors. The array gain offsets some of the attenuation due to narrow electrode spacing. Two additional problems plague surface attached electrodes on a marine mammal. The first is the potential for electrical shorting of the electrodes by the surrounding salt water. To overcome this, we designed electrodes into the suction cups, which are by definition, sealed against the surrounding fluid. To ensure that the electrodes would be pushed against the skin irrespective of the degree of compression of the suction cup, the electrodes themselves are fashioned into small suction cups made of conductive rubber with a compliant mounting. The electrode cup is a snap fit inside the outer cup and so is quick to replace. The second problem with surface electrodes on a free-moving aquatic animal is that relative movement of the electrode on the skin surface creates continuously changing electrical offset voltages that can be much larger than the signal of interest. These offset voltages can be removed by high-pass filtering but the filter must be placed after initial differential amplification of the electrodes to not compromise the noise rejection of the differential processing. This means that the preamplifier stage of the ECG circuit must have both low noise and a wide dynamic range to handle both the weak ECG signal and the large offset voltages. Wide dynamic range is difficult to achieve in a low-power, low-voltage circuit. In the DTAG-3 design, we maximized dynamic range by creating a negative power supply rail for the ECG preamplifier, effectively doubling the range of signals it can handle. To generate the negative supply, a switching circuit is required which generates electrical noise that can couple into the sensitive audio preamplifiers. To avoid this, the supply circuit is switched at the audio sampling rate making it undetectable in the sampled audio signal. The resulting circuit and electrode configuration has been tested in the laboratory and, in various tests on captive animals, but we have not yet had the opportunity to test the final system on free-swimming animals.

Without doubt, we will discover ways to improve the electrode design and signal processing as we gain field experience with the sensor.

Pressure

For the pressure sensor we went to a silicon PCB mount type which saved about 1 gram. The sensor chosen was the Keller TAB1 bridge pressure sensor. Bridge drive was reduced to a constant current source of 0.6 mA, thus reducing the power consumption of pressure measurements. Current supply comes from the battery voltage via a low power MAX9915 op-amp with a drop-out voltage at this current of about 0.2 V. Constant current should be maintained over the full battery voltage range (down to < 3.3V).

The bridge output is amplified by an INA333 instrumentation amplifier with a gain of 20.1x. In keeping with size and weight reduction, the INA133 replaces the AD627 in DTAG-2, which was one of the larger components. The full-scale bridge sensitivity is typically 0.225 V/mA giving 0.135 V full-scale with the bridge current used here. The full-scale voltage level at the output of the instrumentation amplifier is $2.71\text{ V} + V_z$. The reference voltage, V_z , is set to the bridge current sense voltage (0.09V). The instrumentation amplifier is self-zeroing, meaning that it samples and corrects its own offset voltage. To avoid this sampling signal ($\sim 300\text{kHz}$) from entering the ADC, there is a 150 Hz single pole low-pass filter on the instrumentation amplifier output. There is an additional 45 Hz single pole formed by a capacitor across the bridge outputs.

Accelerometer

When designing DTAG-2 there were no viable 3-axis accelerometers available as a single unit. Therefore we included two 2-axis accelerometers and mounted them orthogonally. To do this a custom right angle bracket was fabricated out of aluminum and glued to each accelerometer package. To save weight the new tag moved to a Kionix KXSC7, including 3 axes in a single package. The Kionix KXSC7-1050 $\pm 2\text{ g}$ three-axis accelerometer is a suitable replacement for the composite accelerometers used in the DTAG-2 offering comparable bandwidth and noise floor. In addition to weight and volume reduction, the integrated triaxial accelerometer has lower power consumption (50% saving) and better registration between axes. The accelerometer outputs are low-pass filtered (single pole, $f_c=50\text{Hz}$) and buffered (unity gain) before passing to the sensor ADC multiplexer. Accelerometer output is ratiometric to its supply voltage (VSENSE, 3.0 V) and as the ADC also uses VSENSE as its reference, the sensor scale factor should be fixed. Nominal sensitivity is 600 mV/g, noise level is about $70\text{ }\mu\text{V}/\sqrt{\text{Hz}}$ which should amount to 0.6 mV RMS over the 50Hz bandwidth, equivalent to 1 mg RMS.

Magnetometer

The magnetometer in the new tag is the Honeywell HMC1043 3-axis magnetoresistive bridge driven by a constant current bridge supply. In the new tag, the bridge and instrumentation amplifier are multiplexed to reduce current consumption. The bridge supply is turned on for about 1ms with the instrumentation amplifier disconnected. Sample-and-hold capacitors for each axis are connected to the bridge outputs while it is powered. When the power is disconnected, the capacitors are isolated from the bridge and connected to the instrumentation amplifier in turn. Each capacitor can be connected in the forward or reverse sense allowing in-situ measurement of the amplifier offset voltage. In order for the instrumentation amplifier to settle, about 1 ms per sample was allowed. In between samples, the instrumentation amplifier inputs are connected to

the reference voltage to discharge input and trace capacitances. Careful attention to the voltage potential in these capacitances is essential to reducing errors.

Overall gain of the magnetometer amplifier is 194.4. Output voltage range to the ADC is 1V +/- 1V. The constant current bridge supply to the magnetometer is 6mA and this is sourced directly from the battery. The reference voltage for the bridge supply is 0.09V and this is measured by auxilliary sensor channel MS-. As the magnetometer resistance can vary between 265 and 500 Ohms (all axes in parallel) the bridge voltage will be between 1.59-3.0 V (nominal value 2.0 V). The bridge current is passed by a low resistance MOSFET, so the bridge current should be constant over the full range of battery voltages (i.e., down to VB=3.3 V).

Given the bridge current and the nominal bridge sensitivity of 1.0mV/V/gauss, the magnetometer amplifier output is 3.9 mV/ μ T. Full-scale field range is +/- 250 μ T or +/- 2.5 gauss. The sampling capacitors are chosen for a multiplexer (bridge on/off) duty cycle of 1:4, with an allowable range of 1:3 to 1:5. The raw bandwidth is 230 Hz giving an effective bandwidth after sampling of 230/4 or 57 Hz. The effective noise bandwidth is 360 Hz giving an estimated noise level at the amplifier input of 0.9 μ V RMS. This is well above the amplifier RTI noise so the output noise of the amplifier is dominated by sensor noise of about 0.17 mV RMS equivalent to 44 nT RMS.

Sensor sampling

All sensor channels except the gyroscope are multiplexed to a single analog-to-digital converter to conserve board space and power. If the two ECG channels are sampled at 1kHz and the other sensor channels at 200Hz, the aggregate sensor sampling rate is less than 5kHz allowing a low-power convertor to be used. All of the sensors have a dynamic range << 90dB and so a resolution of 16 bits is adequate if each sensor channel is amplified to fit the input range of the convertor. In a sampled data system, all analog input must have an anti-alias filter before digital sampling. For sensor channels such as accelerometer and magnetometer, which will be integrated in post-processing, it is important to use similar anti-alias filters on each channel to maintain the phase relationships. To minimize circuit area, power consumption, and phase distortion, we used single pole anti-alias filters at 20Hz on each sensor channel making up for the poor stopband frequency response of this type of filter by sampling at a high rate (200Hz). The ECG channels, which will not be integrated with other channels and which require higher bandwidth, have a 2-pole filter at 200Hz which has adequate stopband attenuation for 1kHz sampling. The gyroscopes are located on a separate board, encased in the syntactic foam and so are sampled by a separate ADC. However, the sampling rate and anti-alias filters are identical to those used on the main sensor board.

Body and Shell Construction

DTAG-2 was constructed as an oil-filled shell (figure 25) with a plastic fairing to house the shell and syntactic foam flotation. The circuit cards and sensors were assembled and tested separately and then installed into the shell. A urethane “bag” was then fitted over the shell, sealed and oil filled. The shell was attached to the foam and both were secured inside the plastic fairing. The method for securing and protecting the electronics proved efficient and successful and so it was maintained in the new tag. One necessary improvement, required due to the advent of smaller and thinner PCBs, was to better isolate them from any shell movement due to pressure and/or

temperature effects. Therefore flexible urethane corners were implemented to hold the cards securely while providing some damping effects.

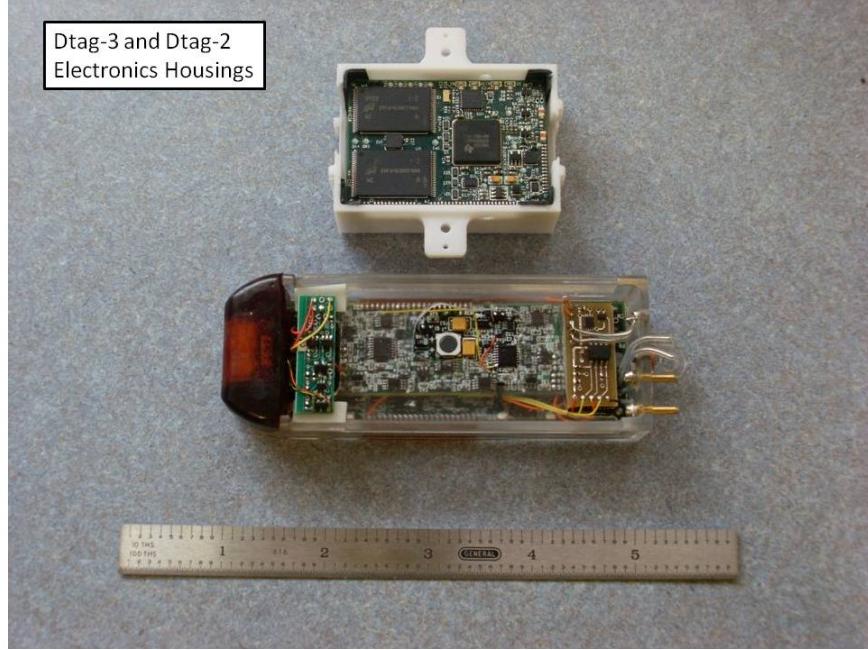


Figure 25. Photograph of the DTAG-3 (top) and DTAG-2 tags (bottom) without their housings.

Another necessary improvement was to further eliminate leakage paths. To achieve this and further reduce overall housing volume, a couple of construction innovations were developed that require a more complicated shell. The main cause of leaks in DTAG-2 was determined to be any wire that allows a direct path from seawater to the oil-filled cavity. So, see figure 26 below, interconnect boards (PCBs) were designed to get wires in and out of the electronics cavity. Circuit boards are made of a glass filled epoxy and provide a very good barrier against seawater intrusion. The interconnect boards allow one side to be inside of the cavity and allow connection to the tag electronics. The other side of the interconnect boards can be wired out to external circuits and sensors. To further bolster this seal and to reduce additional weight we selected an over-potted urethane housing as opposed to a plastic faired housing. Figure 27 shows an assembled body inside the custom DTAG-3 mold, just prior to encapsulating in urethane. By over-potting the outside of the interconnect boards are additionally sealed with urethane providing a double plenum seal effect. It also eliminates the need for additional plastic components creating a more uniform, streamlined and simpler overall shape.

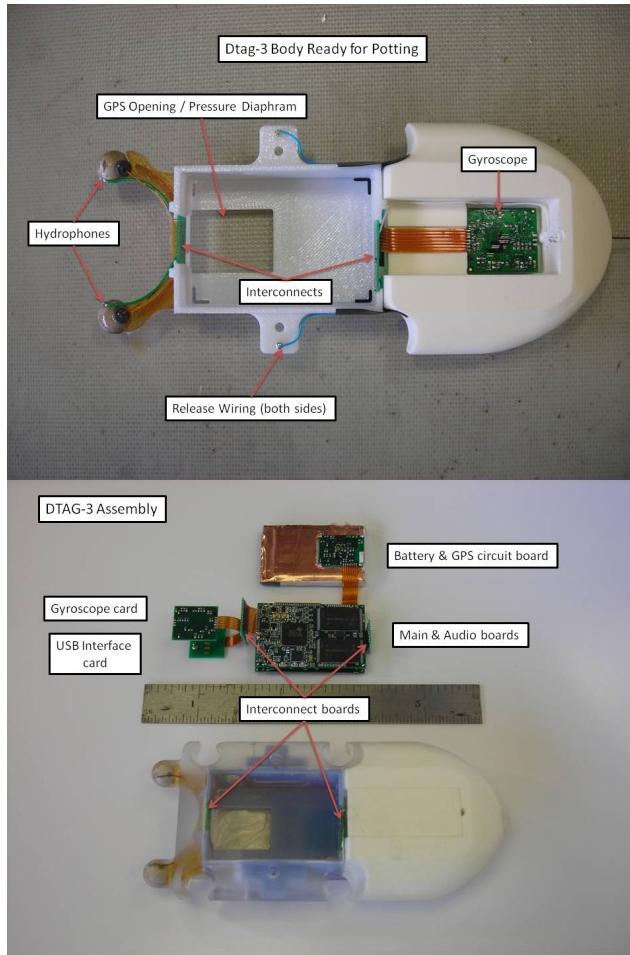


Figure 26. Photograph of DTAG-3 body and assembly.

As stated earlier, the new single pour body required a more detailed shell. The shell has the following requirements: it must house and protect the electronics and battery; interface with outside circuits and sensors; provide a path for environmental pressure (depth measurement); mechanically mount hydrophones, release, flotation and USB interface; provide a means of securing suction cups; provide oil filling ports and anchor points which hold the shell and foam in place while molding. Initially the complex shape was made by Rapid Prototyping to save cost. As will be described later, Rapid Prototype material was not ideal for what we were trying to accomplish with the shell and we ultimately moved to a water-jetted solid plastic shell.

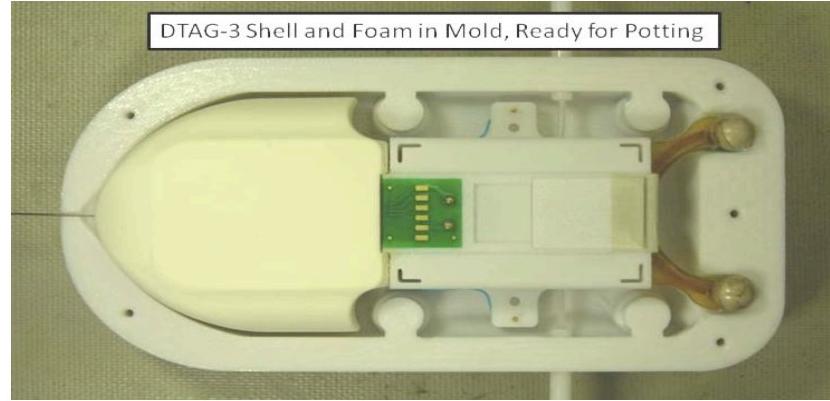


Figure 27. Photograph of DTAG-3 in the mold, ready for potting.

Assembly

Figure 28 shows the components that make up the new DTAG-3. Putting these pieces together is another challenge that benefits from integrated design. How to fabricate, test, calibrate and field ready the new tag requires careful consideration of the order in which the pieces are put together. In parallel with each design step, thought was put into when and how to test components; what needed to be tested prior to body assembly, what needed to be tested after body assembly but prior to final assembly, iterative testing as each body component was wired and how to connect to and seal the electronics cavity.

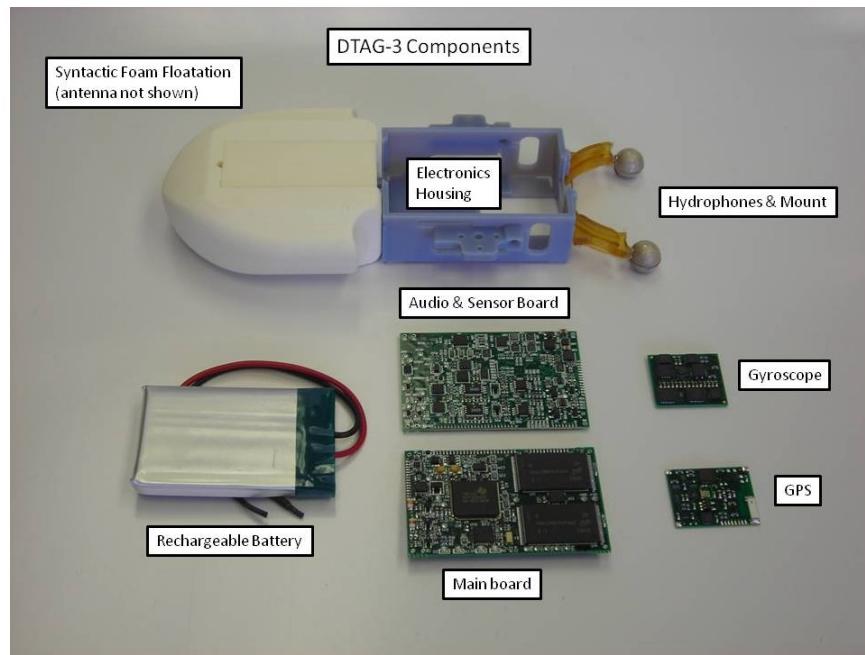


Figure 28. Exploded view of the full DTAG-3

Assembly follows two paths; one for the electronics (main, audio, GPS, gyroscope, USB) and one for the body. The electronics are systematically soldered together and installed into a bench test frame, as in figure 29. Each circuit in the new tag can then be tested and evaluated prior to assembling into the body. Once tested the electronics are folded together and readied to install into the body.

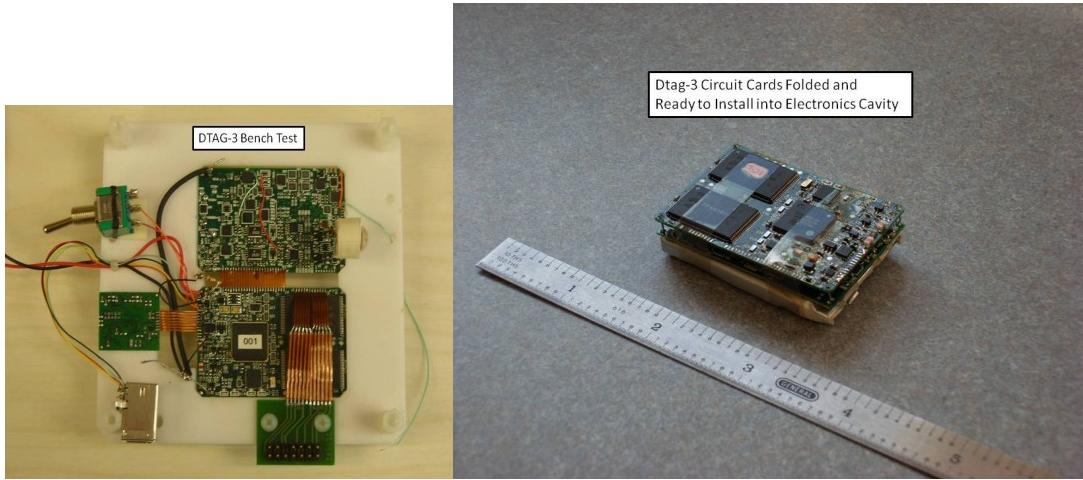


Figure 29. Photograph of DTAG-3 bench test frame (top) and circuit cards ready for installation (bottom).

The body is assembled and wired separately from the electronics testing. Referring to previous figures 25-29, the body assembly steps are as follows:

1. Glue interconnect boards to shell
2. Assemble and test spherical ceramics
3. Glue hydrophones to hydrophone mount, glue mount to shell and wire ceramics to interconnect board, INT-A.
4. Wire and install USB to interconnect board, INT-B.
5. Glue USB interface board to shell
6. Wire and install antenna into foam
7. Test gyroscope circuit board with electronics and then remove for installation here
8. Wire tested gyroscope PCB to interconnect board, INT-B
9. Fit foam to shell and glue, cavity in foam to accommodate gyroscope board
10. Glue foam cover piece in place
11. Wire up release, ECG and ground planes
12. Insert body into mold
13. Pour with urethane

When the body is cured it is removed from the mold and the electronics are inserted, wired and tested. A cover piece is placed over the electronics shell to provide a surface to over pour with urethane thus sealing the unit. The open cavity approach allows the new tag to be assembled as previously described and to be opened and repaired if necessary. The last steps are to fill the cavity with oil and seal the oil fill ports.

Suction Cups and Release

The new tag cups are essentially a scaled down version of the DTAG-2 cups (figure 30). To save weight and provide a more flexible attachment, the rigid stems were eliminated. The result is a single pour cup that is much easier and cheaper to manufacture. Whereas the old cups were attached to the plastic fairing with a stem and cap design, the new cups utilize a shaped head to facilitate mounting. The urethane molded tag body contains a contoured shape and opening that matches the head and stem of the new cup. The cups can then be snapped in place and rotated into the contour to secure. The cups are held in only partially by the body itself and must be further secured with a cover piece. For this we fabricated plastic parts to hold the cups from rotating out of the body, they are secured in place by small screws.

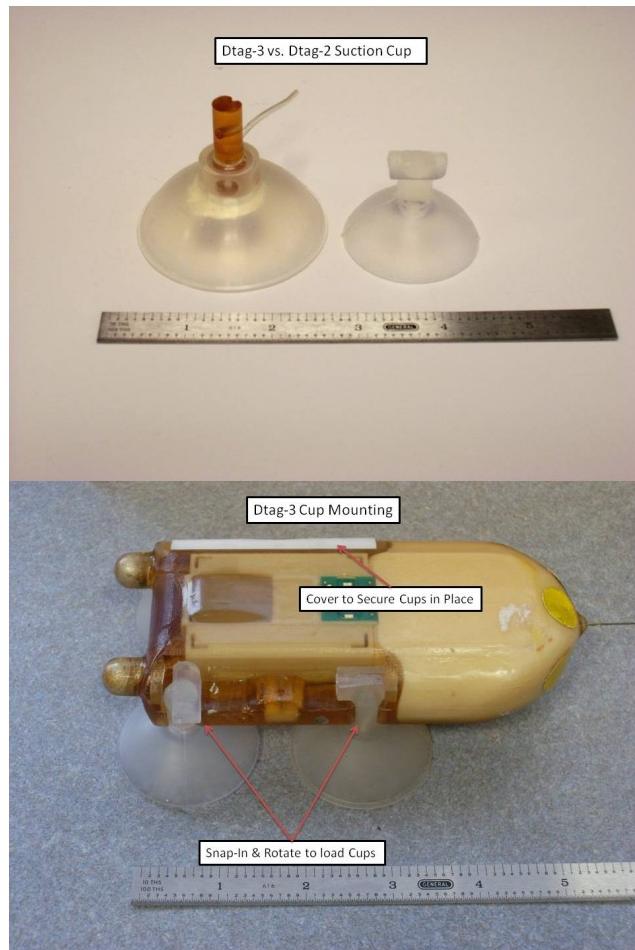


Figure 30. Photographs of DTAG-2 and DTAG-3 suction cups (top) and DTAG-3 with cups mounted (bottom).

The release was executed in a similar fashion to DTAG-2 in that it still requires flooding the suction cups. The leakage path in the new cups is created in the potting process by inserting a piece of tubing in the mold. The tubing defines a channel from the inside of the cup opening through the side of the head. When the cup is cured the tubing is removed and a PVC barb fitting is inserted to provide access to the channel. From this point the two systems are the same;

urethane tubing is fitted over the barb then kinked and passed through a nickel-chromium (nichrome) loop of wire thus holding it closed and sealing the cups. When released the loops are corroded, the tubing opens up and the cups are flooded (figure 31).

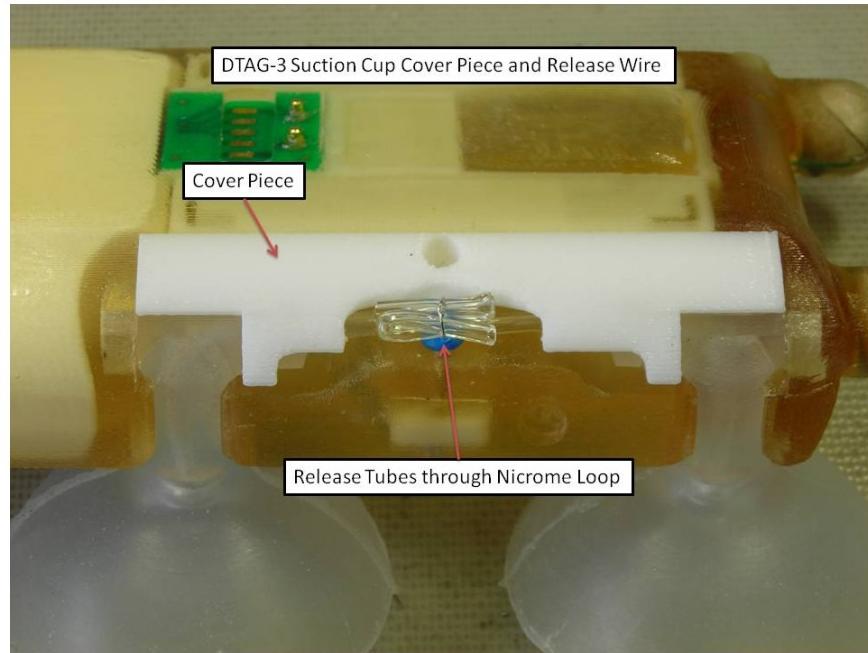


Figure 31. Photograph of DTAG-3 suction cup cover and release wire.

The smaller cups afforded a substantial weight savings. A single DTAG-2 cup with stem weighs 21 grams; a single DTAG-3 cup weighs 8 grams. Since each design requires four cups the total weight savings is 52 grams (figures 32 & 33).

Longer Attachment Results

Figures 32 & 33 summarize the results of the new tag design. The volume was reduced by 50%, recording time was increased to 2 to 4 days and capabilities were not lost, rather they were enhanced. Integrating the design allowed us to combine a set of conflicting goals (low power, reduced size, increased functionality, longer life) and satisfy them all.

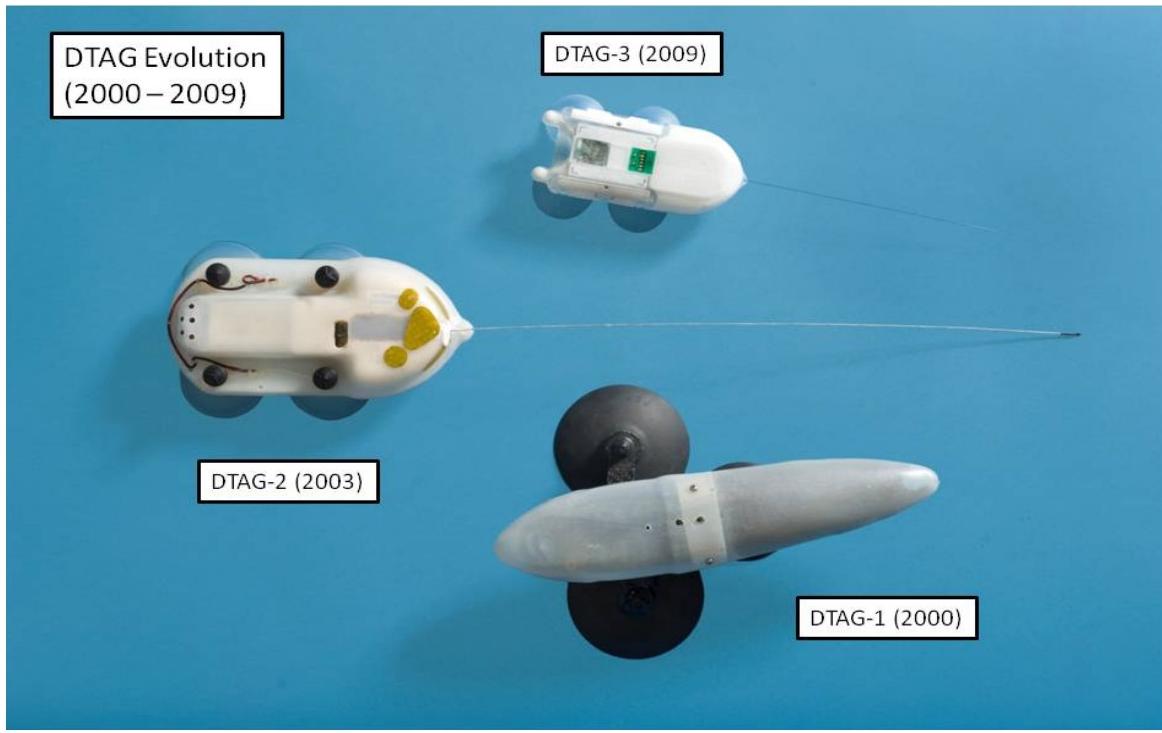


Figure 32. The evolution of different versions of DTAG

Parameter	DTAG2	DTAG3
Volume	400 cm ³	200 cm ³
Weight in air	380 g	190 g
Recording life	18 hrs	2-4 days
Memory	12 GB	32/64 GB
Sampling rate	192 kHz / stereo	240-500 kHz / stereo
Sensors	pressure 3-axis accelerometer 3-axis magnetometer	pressure 3-axis accelerometer 3-axis magnetometer 3-axis gyroscope 2 channel ECG Ultra-fast GPS

Figure 33. Parameters of DTAG-2 and DTAG-3

USB Interface

Cradle design

The new USB user interface with DTAG-3 is much easier and simpler from both a hardware and software perspective. The DTAG-3 USB interface uses a single piece “cradle” interface which, when plugged into a standard USB port, handles all communications (configuration, programming, data setup, data management) and battery charging of the device. The custom designed cradle is shaped to align and clamp to the DTAG-3 body in such a way that it compresses a set of spring loaded contacts thus making electrical connection to the USB interface on the tag (figure 34). When coupled with the custom *d3host* software user interface, DTAG turn-around (i.e., data offloading and battery recharging) during experiments is much simpler and faster. The single cradle replaces 3 components in previous system; the communications infra-red dongle, custom USB infra-red offload box and recharge box. USB offload rates are much faster and more robust as compared to infra-red.

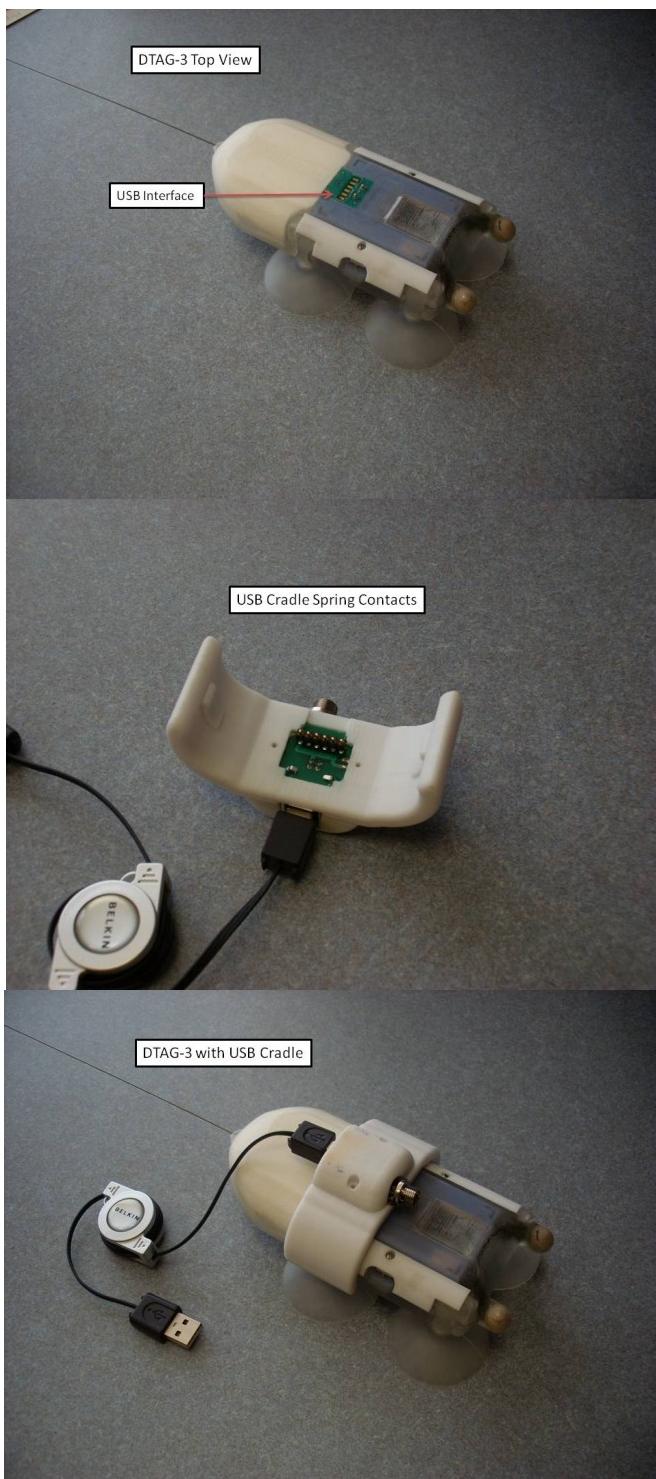


Figure 34. The DTAG-3 USB interface.

Software Design

There are five software components involved in recording and accessing data in the DTAG-3 system. These are:

- 1) executable code for the digital signal processor in the tag. This is the software responsible for configuring sensors and recording data while the tag is attached to an animal. The software is written in C and assembly languages.
- 2) executable code for the low-power wakeup controller in the tag. This software is responsible for the VHF transmitter, suction cup release and time-keeping tasks. It is written in assembly language.
- 3) executable code on a host PC for interfacing to the DTAG-3. This code, written in GNU C, manages the USB interface to the tag and enables data offloading and re-programming of the tag. The software uses a public license USB library.
- 4) executable code on a host PC for unpacking the data obtained from the tag. Data collected by the tag are stored in self-contained archive files which contain error-correction, timing and meta-data information. This file format is appropriate for long-term storage of data and, as the data are compressed, is the most compact way of storing tag data, but the data format is not compatible with standard audio players and data analysis programs. An executable code, written in GNU C, is used to unpack the tag data files to standard formats such as .wav, .xml and text. A public license XML library is used in the software.
- 5) Matlab tools for managing, calibrating and visualizing tag data. Each tag deployment produces a number of files that, together, contain the data collected. Data are spread across files of different sizes and formats to accomodate the constraints of each format and to keep individual file size below the maximum size allowable for each format (e.g., 4GB for .wav format). The Matlab tools present a unified interface to this file set facilitating data access and analysis. The tools include automatic sensor calibration methods that have been distilled from a decade of experience in examining on-animal sensor data.

All of the above software components were present in the DTAG-2 but had to be largely re-written for DTAG-3 on account of the change in interface method (USB instead of infra-red) and complexity of the device. The new tag includes a wider range of sensors than DTAG-2 and these are sampled at a variety of rates and undergo varyious filtering and compression processes before being stored in memory. The simpler sensor layout for the DTAG-2 meant that a simple and reliable lock-step methodology could be used in the tag software. The multi-rate processing in the new tag necessitated a more complex task-scheduling software architecture. The effort of designing this new software was divided between several funded projects reducing the cost to each project. The end result is a flexible environment with well-tested and efficient code modules that will enable rapid and robust re-configuration of the tag as we learn the best sampling strategies for each study species.

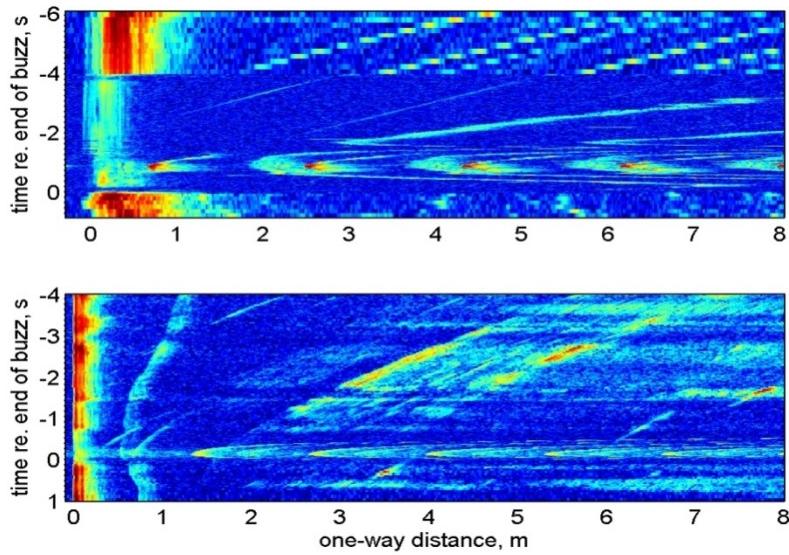
Delivery method and hardware

The DTAG-3 attaches to a pole or air-powered gun via a mounting clamp. The clamp holds the tag until it senses that the cups are attached to a surface. There are several design features in this clamp that are crucial for successful tag deployments. In particular, the clamp must hold the tag securely despite rapid motion of the pole during boat motion or deployment attempts but must

release the tag immediately upon its successful attachment to a whale. Failure of the clamp can lead to lost tagging opportunities. The clamp fits the external form of the tag and so had to be re-designed to accommodate the DTAG-3. A simple lightweight design was tried initially and found to be acceptable in laboratory trials. This design, however, tended to release tags before attachment in the field, making it unsuitable. We have now modified the design of the clamp and will produce a number of improved units for further field testing.

Field testing

The DTAG-3 design has been field tested on four species of marine mammals to date. Results have been very promising but we still lack sufficient deployment numbers to assess the longevity or reliability of the tag attachment. Starting in December 2009, a prototype of the DTAG-3 was tested on captive porpoise in a sea pen at the Fjord & Baelt Center in Kerteminde, Denmark. The objective of this test was to verify high frequency sound recording operation and obtain preliminary data from the movement sensors. The tag was used in two days of fish capture and target selection trials providing excellent recordings until the unit failed due to water ingress. Figure 35 shows the high quality echograms obtained from a porpoise tagged with this tag. The higher dynamic range of DTAG-3 on the bottom cell should be obvious by comparison with the similar spectrogram made from DTAG-2 data from an echolocating beaked whale.



*Figure 35: The DTAG-3 has a wider dynamic range than the DTAG-2, enabling it to acquire both the click made by a tagged whale and more detailed echoes from prey that it ensonifies. Echograms during foraging buzzes (fast series of clicks associated with prey capture attempts) provide a highly detailed view of predator and prey tactics. Upper: Data from a DTAG-2 showing an echogram of a Blainville's beaked whale (*Mesoplodon densirostris*) attempting to capture prey at 600 m depth in the Canary Islands. The prey echo is one of the thin sloping lines while echoes from other organisms complicate the acoustic scene. Lower: echogram of a captive harbor porpoise (*Phocoena phocoena*) capturing dead prey obtained with a DTAG-3. Echoes from the prey are visible during the buzz but echoes from the water surface and the sides of the pool create a complex acoustic scene. Observing bio-sonar foraging using the same tools in the wild and in controlled captive settings will help to interpret this complex behavior and assess the impact of environmental sound on foraging.*

On examination, we found that the cold winter waters had aggravated a weak seam in the urethane over-potting. At this point, we were over-potting prototype tags in two steps to allow for insertion of the electronics at a late stage in the fabrication. This method facilitated parallel fabrication of the body and electronics, and facilitated repair but left a seam where resin from the two potting steps met. After the seam failure, the tag was repaired and trialed for several additional days in the spring without further problem. Trainers working in the captive facility reported that they felt that the animals took well to the tag and displayed unchanged responsiveness to commands, an encouraging result given the small size of porpoise. The first field opportunity on wild animals involved Blainville's beaked whales (*Mesoplodon densirostris*) off the coast of El Hierro in the Canary Islands. A tag was deployed with relative ease on an adult beaked whale which proceeded to carry it for at least 36 hours. Unfortunately, the tag transmitter failed after this time and the full attachment time is unknown. After 5 days, the tag was located off-shore of El Hierro by chance. On examination, we found that water ingress had again caused failure of the recording circuit early in the deployment, and the ingress was pinpointed to another seam in the urethane over-potting. Given these two disappointing failures, we re-evaluated our packaging process and performed peel tests of urethane seams with different surface preparations. We concluded that seams would remain a potential weak point irrespective

of surface treatment and that a seamless package was needed to ensure reliability. To effect this change, we re-designed the electronic cavity, changed the fabrication process and changed the plastic used for this part. This resulted in a sealed plastic box containing the electronic circuits prior to over-potting. The mold was then modified to allow continuous resin flow around the entire cavity. With this modified process, tags are more difficult to repair but contain two full plastic layers preventing water ingress. Two modified tags were pressure tested both in a laboratory facility and by attachment to a 200 m mooring deployed for eight hours without problem. The next field opportunity involved sperm whales off the island of Pico in the Azores. A tag was attached to an adult sperm whale and remained attached for about 6 hours at which point the whale breached and the tag detached. The tag was retrieved without damage other than the loss of a suction cup and a full recording was obtained. The whale made a deep dive to 800 m while the tag was attached but spent most of the attachment time socializing and resting at the surface. Nonetheless, the fact that the tag survived the deep dive and a breach suggests that the water ingress problem may be overcome in the new design although further testing is needed to verify this.



Figure 36. Photograph of a normally surfacing dolphin in Sarasota Bay, moving left to right, wearing a DTAG-3 housing attached with suction cups posterior to the blowhole.
Photograph taken under NMFS Scientific Research Permit No. 522-1785

One of the design goals of the DTAG-3 is that it be small enough and hydrodynamic enough to be used with delphinids including bottlenose dolphins, *Tursiops truncatus*, a species known to react negatively to suction cup tagging (Schneider et al. 1998). Preliminary trials in May 2010 with a “dummy” of the newest version of the DTAG, equipped with a VHF radio transmitter, were highly successful (Figure 36). Three deployments were attempted, and all stayed on the dolphin for at least 2 hours; the one that lasted only 2 hours had a faulty suction cup. Exact durations were not known for the other two tags, since tracking was suspended at sunset after 2.5 and 6.5 hours, and in both cases the tags were retrieved the following morning. Dolphins were followed by trained observers and were behaving normally while wearing the dummy tag: feeding, travelling, and interacting with other dolphins. Thus, we are confident that dolphins will wear the tags for as long as the tags are programmed to last and that the tags will not affect their behavior.

Conclusions and Implications for Future Research/Implementation

This SERDP project has succeeded in meeting its objectives for enabling passive acoustic monitoring of beaked whales on Navy ranges, for studying the effects of the sounds of naval activities on cetaceans, and for developing a new version of the DTAG. Working with NUWC at Newport, we have analyzed data from beaked whales tagged on the AUTEC range to calculate the beam pattern of beaked whales and the probability of detecting beaked whale clicks as a function of aspect and range. We have analyzed the baseline movement, acoustic, and foraging behavior of beaked whales tagged at AUTEC (Johnson et al. 2008). We have collaborated in a large multi-institution Behavioral Response Study using controlled exposure experiments at the AUTEC range to study responses of tagged beaked and other whales to sonar and other sounds (Boyd et al. 2007). This year we have modified the DTAG to make it more suitable to studying effects of actual sonar exercises on cetaceans.

The early results of our effects studies have to be interpreted with care because the analyses are preliminary and the beaked whale playback results stem from just two experiments involving the response of two individuals to a total of three stimuli. There is also a limited set of baseline data to characterize normal behavior. A greater sample size is required before robust conclusions can be drawn. However, the preliminary results help to narrow the high level of uncertainty about the possible responses of Blainville's beaked whales to anthropogenic sound and predator calls, and they suggest that other species of odontocete may respond differently than beaked whales to sonar and other sounds, which may indicate different risks for such exposures for these different species. Taken together these results suggest that beaked whales silence and show avoidance responses to anthropogenic sounds ranging from shipping noise (Aguilar et al. 2006), MFA sonar and PRN in a surprisingly narrow 136-142 dB re 1 μ Pa range. A similar but more intense response was seen in response to the killer whale playback, which was elicited by an exposure at 98 dB re 1 μ Pa, just barely above the ambient noise. After the killer whale playback, the beaked whale had a prolonged post-dive avoidance response. This suggests that while beaked whales showed similar responses to similar exposure levels for anthropogenic sound, they have a stronger response to much lower exposure levels of sounds from a predator. Nevertheless there remains an ambiguity in the interpretation of the killer whale playback; since the killer whale playback was the second in a series on the same animal, it is possible that the prolonged response was a consequence of the second exposure rather than the killer whale waveform. This suggests that carrying out additional anthropogenic sound and killer whale playbacks should be a priority for future work.

Other species tested in playback experiments appear to be less sensitive to anthropogenic and natural sounds than beaked whales. Although reactions were observed in some playbacks, based on the analysis conducted to date, there was little consistency in the responses. This trend suggests further experiments in which the sample size of experiments to test the relative sensitivity of beaked whales and other species to sonar and other sounds can be increased.

The difficulty of building a sample of playbacks for beaked whales contrasts with the relative ease of conducting playbacks with other species. However, one of the most lasting achievements of this project has been to demonstrate that controlled exposure experiments can be carried out on beaked whales and a range of other species without causing serious negative effects. Nothing

in the responses observed to date suggests that the playback experiments presented any risk to the whales. Even though the sample sizes are limited, these beaked whale CEEs have defined a statistically significant response, and have been able to determine the minimum exposure required to elicit the response for each individual and stimulus tested. Now that we have demonstrated that this experimental paradigm can provide useful information without harm or undue risk to the animals, additional results using a similar paradigm are underway.

Additionally, the absence of negative control stimuli for BRS07 means that this test must be repeated with such controls. Comparisons of responses to different stimuli would also allow us to better understand the sound features that elicit responses.

The lessons learned in this process point to a multi-pronged approach using complementary methodologies. The CEE approach is well designed to measure the minimum exposure required to elicit the observed response, to compare whether different stimuli evoke similar responses and if so, whether they require different exposures to evoke the response. The CEE design is also well suited to test for differential responsiveness of different species or age/sex classes or contexts. However, many of the features that enable these capabilities for CEEs make the CEE less like actual exercises. The experience of BRS07 and BRS08 also suggests that it will be difficult to conduct enough CEEs to cover all of the species and stimuli of concern. These considerations all suggest the importance of using the current results to develop innovative new methods to monitor for the effects of actual sonar exercises. Such techniques should be designed for deployment in large numbers and in many situations where anthropogenic sound may cause problems for marine mammals. This SERDP project has demonstrated that a tag that can monitor sound exposure and behavioral reactions is an ideal candidate for such a method.

The DTAG-3 being developed this year with SERDP support will have many of the features desirable in such a tag. The initial tests done by the NUWC group monitoring the locations of echolocation clicks during foraging dives of beaked whales before during and after sonar exercises suggest avoidance responses on the order of days. The new DTAG-3 may just have sufficient attachment duration to measure such effects. However, this would require successful tagging just a day or two before the exercise. The effort by Robin Baird of Cascadia to tag before and during the RIMPAC exercise during the summer of 2008 demonstrates the enormous benefit of using tags that can attach for weeks up to about a month (Mintz and Filadelfo 2010). This enabled Baird to tag an excellent sample size of beaked and other whales. However, the inability of the tags used to measure exposure and behavior have proven a significant obstacle to studying effects of exposure.

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Appendices

List of Scientific/Technical Publications

1. Articles or papers published in peer-reviewed journals

- Ciany, C.M., Rooney III, J., Zurawski, W.C., Tyack, P. 2009. The validation of novel mid-frequency sonar signals design to reduce the impact on marine mammals. *Journal of Underwater Acoustics* 59:47-70.
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- Ward, J., Morrissey, R., Moretti, D., DiMarzio, N., Jarvis, S., Johnson, M., Tyack, P., White, C. 2008. Passive acoustic detection and localization of *Mesoplodon densirostris* (Blainville's beaked whale) vocalizations using distributed bottom-mounted hydrophones in conjunction with a digital tag (DTAG) recording. *Canadian Acoustics* 36:60-66.

2. Technical reports

- Visser, F., Miller, P., Lam, F.P., Kvadsheim, P., Tyack, P.L. 2009. Protocol for Group Behavioural Sampling in Behavioural Response Studies (BRS).
- Boyd, I.L., Claridge, D.E., Clark, C.W., D'Amico, A., Southall, B.L., Tyack, P.L. 2008. Behavioral Response Study 2008 Report. November 2008.
- Boyd, I.L., Claridge, D., Clark, C.W., Southall, B., Tyack, P.L. 2007. Behavioral Response Study 2007 BRS-07 Cruise Report.

3. Conference/Symposium Proceedings

- 2009 Tyack, P.L., Southall, B.L., Moretti, D., Clark, C., Claridge, D., Boyd, I. 2009. Behavioral responses of beaked whales to sound. Paper for ECS 2009 Workshop on Beaked whales and active sonar: transiting from research to mitigation, 28 February 2009, Istanbul Turkey.
- 2008 Tyack, P.L., Johnson, M., Madsen, P.T., Zimmer, W.M.X., Aguilar de Soto, N., Bocconcelli, A., Miller, P.J.O. 2008. How to get a tag to sense like an animal. Proceedings from the Animal-borne Imaging Symposium, National Geographic, Washington DC.
- 2006 Tyack, P.L., Johnson, M.P., Aguilar de Soto, N., Madsen, P.T. 2006. Acoustic behavior of beaked whales, with implications for acoustic monitoring. Proceedings of the IEEE Oceans06 Conference.

4. Conference/Symposium Abstracts

Acoustic response and detection of marine mammals on navy ranges using a digital acoustic recording tag. SERDP Scientific Advisory Board Meeting, Aberdeen MD, 13–14 June 2006
Acoustic behavior of beaked whales, with implications for acoustic monitoring. Oceans06, Boston, 21 Sept 2006

Research Protocols – Behavioral Response Study. Ad hoc working meeting on the planning for controlled exposure experiments with deep diving odontocetes (esp. beaked whales), Arlington VA, 26 October 2006

Beaked whales and sonar. NATO Naval Group 2, Ad hoc Working Group on Marine Mammal Protection, La Spezia Italy, 14 December 2006

Effects of sonar on beaked whales. Deputy Assistant Secretary of the Navy for Installations and Environment. Washington DC, 7 February 2007

Effects of sonar on beaked whales. US Navy Fleet Forces Command. Norfolk VA, 7 February 2007.

Research protocols for Behavioral Response Study. Meeting of Science Advisory Board of Behavioral Response Study, National Marine Mammal Lab, Seattle WA, 26-28 March 2007

How beaked whales echolocate to find, select, and capture prey. NOAA Acoustics Program Lecture Series, Duke University, Raleigh North Carolina, 24 April 2007

How toothed whales echolocate to find and capture prey in the deep ocean. Lowell Lecture Series, New England Aquarium, Boston, 14 May 2007

How deep diving odontocetes echolocate to forage. Boston Behavior Club Symposium, Woods Hole, 26 May 2007

Study on behavioral responses of tagged beaked whales to anthropogenic and natural sounds.
Intergovernmental Conference: The Effects of Sound in the Ocean of Marine Mammals, Lerici (SP), Italy, 11 - 15 June 2007

Military training impact on beaked whales. 2007 Sustaining Military Readiness Conference, Orlando FL, 2 Aug 2007

How marine mammals adapt to noise. International Ethological Conference, Halifax, Nova Scotia, 22 August 2007

The importance of audio in animal borne instrumentation. Animal Borne Imaging Symposium, National Geographic Society, Washington DC, 13 October 2007

Behavioral Response Study, Acoustics meeting, Sea Mammal Research Unit, St Andrews, Scotland, 21-22 Jan 2008

Passive acoustic monitoring for marine mammals, Norwegian Defense Research Institute, Horten, Norway 23 January 2008

Marine mammal behavioral studies. talk to House Armed Services Committee staffers, WHOI, 22 February 2008

Marine mammal talk for WHOI trustees, WHOI, 16 May 2008

Tags, behavior, BRS. US Navy ICG, WHOI, 20 May 2008

Plenary speaker, How sound from human activities affects marine mammals, 30 June 2008, Acoustics08, Paris France

Effects of sound on the behavior of toothed whales. Peter Tyack, Ian Boyd, Diane Claridge, Christopher W. Clark, David Moretti, and Brandon Southall, Acoustics 08, 30 June 2008

How toothed whales echolocate to find and capture prey in the deep ocean. Peter Tyack, Mark Johnson, Peter T. Madsen, Walter M. Zimmer, and Natacha A. Soto, Acoustics08, Paris, 2 July 2008

How toothed whales echolocate to forage. Summer Student Fellows, WHOI, 7 July 2008

Plenary speaker, Use of vocal production learning to compensate for varying noise or competing signals, Vocal Communication in Birds and Mammals University of St Andrews, 31 July-2 August 2008

Plenary speaker, Using tags for continuous sampling of the behavior of animals – examples from deep diving toothed whales, Third International Biologging Science Symposium, Asilomar, Pacific Grove, CA, 4 September 2008

Effects of sonar on marine mammals. Naval Command College, WHOI, 19 Sept 2008

Effects of Sonar on Marine Mammals. presentation to staffers for Senate Commerce Committee, Woods Hole, 12 November 2008

Studying responses of beaked and other whales to sonar and other sounds. Tyack poster at SERDP/ESTCP Symposium, Washington DC, 3-4 December 2008

Acoustic Tag Developments and Updates on Behavioral Response Studies, Tyack talk at technical session “Marine Mammals and Military Operations” at Partners in Environmental Technology Technical Symposium & Workshop. Washington DC, 3-4 December 2008

Studying effects of sonar on toothed whales. NMFS Office of Protected Resources, Silver Spring MD, 2 December 2008

Marine Mammals and Noise, focusing on beaked whales and military sonar. Brief to the Spanish Ministries of Defense, Environment and Fisheries, Madrid, 29 January 2009

Behavioral responses of beaked whales to sound. ECS Workshop on beaked whales and active sonar, 23rd Annual conference of the European Cetacean Society, Istanbul Turkey, 1 March 2009

Beaked whales respond to navy sonar. 23rd Annual conference of the European Cetacean Society, Istanbul Turkey, 3 March 2009

Behavioral responses of beaked and other whales to sonar and other sounds. Brief to Chief of Naval Research, Woods Hole, 25 March 2009

Development of acoustic tags and early beaked whale results. International BRS workshop, Lerici Italy, 14 April 2009

Summary of BRS-07/08 results. International BRS workshop. Lerici Italy, 14 April 2009

Procedure & Protocols – Behavior, group lead and presenter, International BRS workshop, Lerici Italy, 15 April 2009

Acoustic response and detection of marine mammals on navy ranges using a digital acoustic recording tag. SERDP In Progress Review, Arlington VA, 30 April 2009

How sound from human activities affects marine mammals. WHOI Journalists, Woods Hole, 1 May 2009

Behavioral responses of beaked whales to sound. presentation to visitors from Naval Oceanographic Office, Woods Hole, 19 May 2009

Effects of sonar on marine mammals. Naval Staff College, Woods Hole, 27 May 2009

How sound from human activities affects marine mammals. presentation to Naval Oceanographic Office visitors Captain James Berdegeuz, Kenneth Sharp and Peggy Schexnayder, WHOI, 11 June 2009

Integrated multi-scale experimental and opportunistic study on effects of sonar on beaked and other toothed whales. 3rd Intergovernmental Conference on The Effects of Sound in the Ocean of Marine Mammals, 7–9 September, 2009, Lerici (SP), Italy

How sound from human activities affects marine mammals. WHOI Science Journalism Fellows, WHOI, 17 September 2009

Beaked whales respond to sonar. presentation to Deputy Undersecretary of the Navy William Natter, WHOI, 6 Oct 2009

Effects of sonar on beaked and other toothed whales. presentation to Adm Wisecup, president US Naval War College, WHOI, 8 Feb 2010

How toothed whales echolocate to find and capture prey. Biology Department talk, Pomona College, Claremont CA, 23 March 2010

How sound from human activities affects marine mammals, talk to Esty Group, WHOI, 31 March 2010

Using electronic tags to discover how toothed whales echolocate to find and capture prey in the deep ocean. Bio-X Lecture, Stanford University, 15 April 2010

Dive patterns of beaked whales (with brief consideration of sperm and pilot whales). Workshop on Gas Kinetics of Diving Marine Mammals, Woods Hole MA, 27-29 April 2010

Effects of Sonar on Marine Mammals, Presentation to Naval Staff College, Woods Hole MA, 3 June 2010

Using electronic tags to discover how toothed whales echolocate to find and capture prey in the deep ocean, Talk to WHOI Summer Student Fellows, 26 July 2010

Effects of Sonar on Marine Mammals, presentation to visitors from Instituto de Estudos do Mar Almirante Paulo Moreira (IEAPM), Brazil, in Woods Hole, 1 October 2010

5. Published Text Books or Book Chapters

- Tyack, P.L., Johnson M., Madsen,P.T., Zimmer M.X., Aguilar de Soto N., Bocconcini A., Miller P.J.O.M. 2008. How to get a tag to sense like an animal. Proceedings from the Animal-borne Imaging Symposium, National Geographic, Washington DC.
- Hindell, M.A., Crocker, D., Mori, Y., Tyack P. 2010. Foraging behaviour. Chapter 11 in Marine Mammal Ecology and Conservation: A handbook of techniques. (Boyd, I., Bowen, D. and Iverson, S. eds.) Techniques in Ecology and Conservation Series, Oxford University Press.
- Tyack, P. 2008. Effects of sound in the ocean. In: Atlas of the Ocean, National Geographic Society, Washington D.C.

Other Technical Material

1. Protocols

Group Behavior Sampling Protocol in Behavioural Response Studies (BRS)

2. EPA/State Regulatory Permits

NMFS Permit # 981-1707-00

NMFS Permit # 1121-1900

NMFS Permit # 14241

3. Awards

2006 SERDP Project of the Year – Sustainable Infrastructure, Acoustic Response and Detection of Marine Mammals Using an Advanced Digital Acoustic Recording Tag

4. Scientific/technical honors received

Director, WHOI Marine Mammal Center, 2008